Investigation of the Impact of Desalination on the Salinity of the Persian Gulf

by

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Abstract

The Persian Gulf (also known as the Arabian Gulf) is a shallow marginal sea located in a region of Southwest Asia with arid climate. Because of this aridity, evaporation from the Gulf is extremely high (1.84 meters per year) and far exceeds the sum of freshwater inflow to the Gulf, mainly from precipitation and some from river flow. A residual circulation exists between the Gulf and the Indian Ocean such that saline water flows into the Gulf from the Indian Ocean in order to balance the freshwater deficit due to high evaporation rate; and since evaporation only removes freshwater, the salt associated with this inflow from the Indian Ocean is removed in dense saline water that naturally sinks to lower layers and exits the Gulf into the Indian Ocean. The Gulf is also the source of seawater and sink of hypersaline effluent (brine) for many desalination plants representing about 50% of the world’s seawater desalination capacity, because many of the countries on the Gulf have increasing human populations but no renewable freshwater resources. It has been recognized long ago that the impact of brine discharge on the Gulf cannot be discussed separately from the dynamics of the residual circulation, but to date there is no basin scale environmental analysis for the impact of seawater desalination activity on the Gulf.

A coupled Gulf-Atmosphere Regional Model that simulates the residual circulation between the Gulf and the Indian Ocean is used to investigate the impact of desalination on the salinity of the Gulf. Satellite data on sea surface temperature and water surface elevation are used to constrain the model, and to analyze trends in the Gulf. Four main contributions of this thesis are emphasized. First, the equilibrium state variables describing the Gulf are identified, including a new estimate of Gulf basin salinity of $40.5 - 41$ g/kg. Second, it is shown that desalination has minimal impact on salinity averaged at the basin scale but significant impact at regional scale. Changes in regional salinities are used to quantify the impact of desalination in different regions within the Gulf. Third, a specific criterion for placement of brine discharge systems in the Gulf that minimizes regional salt accumulation is proposed in order to guide planning and design of future seawater desalination plants, as well as management of existing plants. Lastly, trend analysis shows a small trend in sea surface temperature ($\approx 2^\circ C$ during 1993 - 2014), most likely caused by climate change, but slight trends in Gulf basin salinity that are likely due to natural variability.
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Chapter 1

Introduction

1.1 The Water Resource of the Persian Gulf

Figure 1-1: World climate zones.

The Persian Gulf (hereafter "Gulf") is a shallow (mean depth $\approx 35$m) marginal sea located in the region of Earth north of the Equator where the climate is hot and arid (Fig. 1-1). Because of this climate, evaporation from the Gulf is very high ($\approx 1.84$ m/yr) and far exceeds the sum of freshwater inflow from precipitation and river runoff into the Gulf ($\approx 0.22$ m/yr), and consequently, the salinity of the Gulf is very high ($\approx 40.5 - 41$ g/kg) since evaporation removes only freshwater. Furthermore, a non periodic circulation between the Gulf and the
Table 1.1: Population, urban population, renewable internal freshwater resources (RIFR) per capita for the 7 countries with coast on the Persian Gulf (World Bank, 2014, 2016).

<table>
<thead>
<tr>
<th>Country</th>
<th>Population (10^3)</th>
<th>Urban Pop. (%)</th>
<th>RIFR/capita (m^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bahrain</td>
<td>1,425.17</td>
<td>89</td>
<td>3</td>
</tr>
<tr>
<td>Iran</td>
<td>80,277.43</td>
<td>74</td>
<td>1,639</td>
</tr>
<tr>
<td>Iraq</td>
<td>37,202.57</td>
<td>70</td>
<td>1,009</td>
</tr>
<tr>
<td>Kuwait</td>
<td>4,052.58</td>
<td>98</td>
<td>0</td>
</tr>
<tr>
<td>Qatar</td>
<td>2,569.80</td>
<td>99</td>
<td>0</td>
</tr>
<tr>
<td>Saudi Arabia</td>
<td>32,275.69</td>
<td>83</td>
<td>2</td>
</tr>
<tr>
<td>UAE</td>
<td>9,269.61</td>
<td>86</td>
<td>0</td>
</tr>
</tbody>
</table>

Indian Ocean, often called “residual circulation,” brings saline water from the Indian Ocean into the Gulf to balance the freshwater deficit due to evaporation (≈1.62 m/yr) and removes the salt associated with this inflow into the Gulf back to the Indian Ocean. But due to the scarcity of freshwater resources such as precipitation, river runoff and groundwater in most of the countries with coast on the Gulf (Tab. 1.1), desalinated water is a major component of the freshwater budget of these countries, and the Gulf is the source of seawater and sink of hyper saline discharge (brine) for desalination plants producing ≈50% of the world’s seawater desalination capacity.

Desalination is vital to the hydrology of the Gulf because the people in most of the countries with coast on the Gulf (Tab. 1.1) depend on its water resource for potable water. And discharge of brine from desalination plants into the Gulf can lead to costly environmental problems in the marine environment because brine, in addition to its high temperature and salt content (≈1.5×ambient salinity), also contains antifouling and cleaning agents such as chlorine and chlorinated hydrocarbons, and metal ions such as Copper (Cu), Nickel (Ni), Iron (Fe), Chromium (Cr) and Zinc (Zn). But unlike salt that is a property of seawater, some constituents of brine are foreign to the marine environment and toxic to marine biota and humans. And the concentrations of the metal ions in brine are much higher than ambient concentration levels, which poses significant risk to marine biota because some of these metals become toxic at relatively lower concentration levels (Al-Awadhi, 1999).

The first commercial seawater desalination plant in the Gulf was built in Kuwait in 1957 (Temperley, 1980) and there are more than 850 seawater desalination plants of various
capacities currently online or under construction in the Gulf (Global Water Intelligence, 2016). And investigators recognized long ago that the effect of seawater desalination on the Gulf, at basin and regional scales, cannot be discussed separately from the mechanics of the residual circulation between the Gulf and the Indian Ocean.

However, although detailed environmental impact analysis is crucial to planning, design and management of seawater desalination plants in order to avoid costly environmental problems and minimize cost (Hopner and Windleberg, 1996; Morton et al., 1996; Einav and Lokiec, 2003), there is no basin scale environmental analysis for the impact of seawater desalination on the Gulf. And a recent review study of regional impact analysis by some coastal countries in the Gulf (Reynolds, 1993) highlights the scarcity of quantitative peer reviewed studies that are useful for design, placement and management of desalination plants (Roberts et al., 2010).

The goal of this thesis is to investigate the impact of seawater desalination on the salinity of the Gulf and quantify, using basin and regional salinities, the interaction between brine discharge from seawater desalination plants and the residual circulation between the Gulf and the Indian Ocean. And since salinity maybe considered as a tracer, this investigation subsumes investigations of the basin and regional accumulation of the other chemical constituents of brine such as chlorinated hydrocarbons and metal ions.

1.2 Outline of Work

The four objectives of this thesis are (Fig. 1.2): 1) use a coupled Gulf-Atmosphere Regional Model (GARM) to simulate the dynamics of the residual circulation between the Gulf and the Indian Ocean, and identify the equilibrium properties of the Gulf; 2) introduce brine discharges from seawater desalination plants into the dynamics of the residual circulation in the Gulf and quantify the effect of brine discharges into the Gulf from seawater desalination plants at the basin and regional scales; 3) evaluate the placement of brine discharge point in seawater desalination plants in the Gulf that minimizes regional salt accumulation that leads to increase in basin and regional salinities; 4) use observed and satellite derived data to analyze trends in equilibrium properties of the Gulf. Inshore water bodies and characteristics
of residual circulation are reviewed in the rest of this chapter, and the physical geography, atmosphere in the Gulf region and physical oceanography of the Gulf are described in chapter two. Objective one is reported in chapters three and four, and objectives two, three and four are reported in chapters five, six and seven respectively. And lastly, a summary of this investigation is given in chapter eight with a discussion of the future of the Gulf.
1.3 Classification of Estuaries

Inshore water bodies such as bays and estuaries represent a small percentage of ocean waters, but these shallow water bodies are much more important compared to the deep ocean with regards to human food production and other human uses. And this is because more than sixty percent of the world’s population resides near inshore waters where the seafood obtained from these waters represents a major source of daily sustenance (Stommel, 1951; Pritchard, 1952). Furthermore, majority of the world’s ports and harbors are located in inshore water bodies, which has greatly increased the pollution and degradation of these systems; and as seawater desalination becomes more economically viable, freshwater demand from inshore water bodies has increased significantly. Because urban development and other human uses have increased the stress on inshore water bodies, the response of these water bodies to a changing climate is also an urgent concern (Richard A. Nunes-Vas, 2012).

Hydrodynamic systems such as estuaries can be classified based on the predominant physical mechanisms of motion and mixing of water in the estuary (Stommel, 1951), and the two subsets of estuaries are classical (positive) estuaries, found in wet climates, and inverse (negative) estuaries, found in hot and arid conditions.

1.3.1 Classical (positive) Estuaries

According to Pritchard (1952), an estuary is a “semi-enclosed coastal body of water having a free connection with the open sea and containing a measurable quantity of sea salt.” Classical estuaries have historically been used to describe inshore water bodies with a “measurable dilution” of seawater by runoff water from land. Classical (or positive) estuaries are uniquely identified by certain features: first, because seawater has a higher salt content (salinity) than runoff water from land, the salinity in a classical estuary increases from the estuary head, where runoff water enters an estuary, toward the estuary mouth, where the estuary water meets the open ocean. Since the difference in salinity between runoff water from land and seawater implies that seawater is denser (heavier) than runoff water, runoff water has a tendency to float on top of seawater in a positive estuary and this pattern of stratification is often described as the input of “positive buoyancy” into the estuary; the second feature that
characterizes classical estuaries is that the introduction of buoyancy occurs at a point source (or sources) where runoff water from land meets with seawater (Nunes-Vas et al., 1990).

1.3.2 Inverse (negative) Estuaries

An inverse estuary is a subset of estuaries where evaporation from the estuary surface exceeds the sum of runoff water from land and precipitation that enters into the estuary. (Pritchard, 1952). Inverse estuaries are characterized by certain distinguishing features; first, like classical estuaries, buoyancy is introduced into the inverse estuary due to evaporation, however, unlike classical estuaries, it is “negative buoyancy” that is input into inverse estuaries because when water evaporates from an inverse estuary, the density of the surface layers increases over that of the layers below due to (a) the residual weight of the salt left behind in evaporation and (b) evaporative cooling due to the removal of latent heat of evaporation. And the colder heavier surface layers sinks to the bottom of the inverse estuary (de Silva Samarasinghe and Lennon, 1987; Phillips, 1966). Second, salinity in an inverse estuary increases from the estuary mouth toward the estuary head. And third, the input of negative buoyancy, to first order, is uniformly distributed across the surface of the inverse estuary because evaporation, to first order, is uniform over the surface of the inverse estuary (Nunes-Vas et al., 1990).

The fourth distinguishing feature from which the name “inverse estuary” is derived is that, unlike classical estuaries where net water flow is toward the estuary mouth, in order to conserve mass in inverse estuaries, the freshwater lost to evaporation must be replaced by water flowing from the open ocean (estuary mouth) toward the estuary head (de Silva Samarasinghe and Lennon, 1987). But as defined, the inverse character of an inverse estuary need not persist permanently in space and time because seasonal rainfall can provide freshwater which may reverse the status of an inverse estuary to that of a classical estuary. And evaporation may progressively diminish advection of freshwater within an estuary so that at some distance from the estuary head evaporation exceeds freshwater input and both classical and inverse estuary status prevail within the same estuary system (Nunes-Vas et al., 1990).

Evaporation driven inverse estuaries such as the Persian Gulf, Red Sea and Spencer Gulf occur in the subtropical belt of the northern and southern hemispheres where arid conditions prevail, evaporation rates are high, and precipitation rates are low (Nunes-Vas et al., 1990;
Reynolds, 1993). Moreover, the subtropical arid belts correspond to the sinking branch of the Hadley Cells (HC), the primary circulation in the atmosphere that equilibrates the incident solar energy that reaches the earth’s surface. The HCs are characterized by rising of moist air near the equator (rising branch), poleward flow in the tropical upper troposphere that carries heat, descending motion of cold air (sinking branch) in the subtropics, and equatorward flow in the boundary layer (Fig. 1-3). In the rising branch of the HC, moist air converges near the equator and deep convection transports the water vapor upward; the water vapor adiabatically cools, saturates and precipitates, and dry warm air, due to retention of latent heat, moving poleward subsides in the sinking branch of the HC in the subtropical dry zone (Holton, 2004).

1.4 Properties of Inverse Estuaries

1.4.1 Forcing

The forces that provide the kinetic energy and determine the dynamics of an inverse estuary can be partitioned among three processes: tidal forces, wind forces and pressure gradient forces due to evaporation induced buoyancy flux across the surface layers of water in the inverse estuary. Tidal forces have a time scale of a few hours and diurnal or semi-diurnal periods, and wind forces develop and subside over a few days. In contrast, evaporation induced...
pressure gradient forces have a time scale of several weeks and may prevail permanently due to the longer period before the inverse estuary responds to seasonal forcings such as precipitation, air temperature and evaporation (Reynolds, 1993). Although wind and tidal forces play an important role in the dynamics of inverse estuaries, pressure gradient forces are the primary source of kinetic energy that drives the circulation between an inverse estuary and the open ocean (Hunter, 1983).

1.4.2 Pressure Gradient Force

Due to its longer time scales and non periodic nature, pressure gradient force induces what is often called a “residual circulation,” which transports mass and heat from the inverse estuary into the open ocean. And it is in this sense that the residual circulation is the oceanic counterpart of evaporation, which transports mass and heat into the atmosphere. Recall that evaporation from the surface of an inverse estuary removes water vapor and latent heat from the surface layers, resulting in colder denser waters at the surface layers that sink to the bottom of the inverse estuary; and a horizontal pressure gradient force arises due to the difference in density between the sinking waters and waters in the intermediate and bottom layers of the inverse estuary that induces motion in the direction of pressure gradient force i.e. in the direction of the estuary mouth (Hunter, 1983; Phillips, 1966).

1.4.3 Kinematics of Residual Circulation

Fig. 1-4 shows a schematic of the longitudinal section of a simple two layer system in an inverse estuary. In layer one there is a net horizontal flow toward the estuary head in order to replace the mass removed by evaporation, and denser colder waters sink into layer two and the density difference between the waters of the two layers generates a net horizontal flow toward the estuary mouth. Moreover, the depth and slope of the interface between layer one and layer two vary longitudinally and laterally due to seasonal fluctuations in evaporation and the distribution of salinity within the basin. However, since the water flowing into the inverse estuary in layer one is less saline than the water flowing out in layer two, there must be a flow of salt through the interface from layer two into layer one in order to maintain salinity
continuity. Hence, there is a net negative vertical velocity across the interface between the two layers (Pritchard, 1952). The strength of the residual circulation in different regions of the inverse estuary is correlated with the distribution of salinity since the highest salinity fluids, to first order, are those which have experienced the most extended isolation from mixing and mingling with waters from the open ocean (Nunes-Vas et al., 1990). Therefore, a small (large) salinity gradient between waters in an inverse estuary and the open ocean suggests a stronger (weaker) circulation.

1.4.4 Tidal Dynamics & Coriolis Effect

Tidal dynamics regulate tidal mixing, the stirring and mixing of water, and vertical stratification in an inverse estuary, but tides do not make an important contribution to the residual circulation (de Silva Samarasinghe and Lennon, 1987; Reynolds, 1993). And the effect of tides is further modulated by the geometry and depth profile (bathymetry) of an inverse estuary because shallow (deep) inverse estuaries tend to be less (more) stratified in the vertical. However, when the estuary mouth is narrow, relative to the average width of the basin,
Figure 1-5: Schematic presentation of lateral structure of residual circulation in Northern Hemisphere; x and y are the longitudinal and latitudinal extensions respectively.

tidal velocities are large in and near the estuary mouth but become relatively small within the inverse estuary, which tends to weaken the effect of tidal mixing towards the estuary head (Pritchard, 1952; Stommel, 1951).

The Coriolis Effect due to the earth’s rotation tilts the surfaces of equal density (isopycnals) and deflects the less dense inflowing waters from the open ocean and denser outflowing waters from the inverse estuary. And this leads to a lateral salinity gradient and lateral structure in the residual circulation (Phillips, 1966; Pritchard, 1952). The resulting lateral structure of the residual circulation is cyclonic (Fig. 1-5-1-6), which is counterclockwise circulation in the northern hemisphere and clockwise circulation in the southern hemisphere (Spall, 2004). But the magnitude of the Coriolis Effect depends on the meridional (north-south) extent of an inverse estuary, with small (large) meridional extent implying a weak (strong) Coriolis Effect (Zhai, 2014).
Figure 1-6: Schematic presentation of lateral structure of residual circulation in Southern Hemisphere; x and y are the longitudinal and latitudinal extensions respectively.
Chapter 2

The Persian Gulf

2.1 Physical Geography

The Gulf region is a low lying area enclosed by several mountain ranges and a desert. The Taurus Mountain range in southern Turkey, Pontic Mountains in northeastern Turkey and the Caucasus Mountains in Georgia have a general range of 9000 - 12000 ft, and they enclose the Gulf in the northwest and north respectively (Perrone, 1979); the Zagros (Fig. 2-1) Mountain range on the eastern side of the Gulf, which has a general elevation of 6000 - 9000 ft, runs parallel to the Persian Coast of the Gulf. And the distant effect of these mountain ranges is to provide an effective barrier to all but the the strongest winds which brings cold air from the north into the Gulf region. But the Al Hajar Mountains in the southern part of the Gulf in eastern Oman are lower in elevation (general elevation 3000 - 6000 ft) and they modulate the exit of winds out of the Gulf. The overall effect of the topography in the Gulf (Fig. 2-1) is to orient the air flow in a northwest - southeast direction i.e. along the longitudinal axis of the Gulf (Perrone, 1979).

The main topographic feature at the estuary head is the Tigris-Euphrates-Karun River Delta or Shatt al Arab. These three rivers have their watersheds far into the Taurus and Zagros and they are the three largest sources of freshwater into the Gulf, but there are also numerous smaller rivers that drain the Zagros Mountains on the Persian Coast and deliver small amounts of freshwater into the Gulf (Reynolds, 1993). However, the Gulf is bounded on the west and south by a desert, and unlike its eastern and northern side, there is no
Figure 2-1: Physical geography of the Persian Gulf; the Gulf is surrounded by land except at the Strait of Hormuz (SH) that connects the Gulf with the Indian Ocean.

freshwater reaching the west-southwestern coast i.e. Arabian Coast (Evans et al., 1973).

2.2 The Atmosphere

2.2.1 Regional Climate

The Gulf is located in the subtropical belt of the Northern Hemisphere characterized by the sinking branch of the Hadley Circulation (HC). The regional climate is hot and arid and annual rainfall ranges from 5 to 7 cm, all of which falls within a period of two to three weeks. The air that descends over the Gulf is the poleward moving dry warm air in the HC, due to retention of latent heat after the moisture in the HC precipitates; winter temperatures may
descend as low as 0 °C while summer air temperature frequently reaches 40 – 50 °C, and an air temperature of 87 °C has been recorded in the region (Wilson, 1927; Purser and Siebold, 1973; Reynolds, 1993). But the atmosphere over the Gulf is continental because the Gulf is almost completely surrounded by land (Fig. 2-1) and has a strong land-sea breeze circulation that prevails throughout the year (Eager et al., 2008). The Gulf also experiences marked intra-annual variability in atmospheric climatic factors such as evaporation, air temperature, and winds, and it is the combined effect of strong winds, high temperatures and dry air that leads to the high evaporation rate in the Gulf (Purser and Siebold, 1973).

The dominant and most frequent wind in the Gulf that blows in the northwest-southeast direction (along the longitudinal axis of the Gulf) is called the Shamal, derived from the Arabic word for both “left” and “north” (Nuemann, 1977). This wind is preceded by a cold frontal passage and accompanied by thunderstorms, low visibility from dust storms, and high seas. And a smaller wind system called kaus precedes the arrival of the Shamal and blows from the southeast (Reynolds, 1993). The summer Shamal from June to mid July blows with less interruption and is less significant in terms of wind strength and associated weather conditions. But the winter Shamal from November to March produces the strongest winds and large waves in the Gulf, and the duration of these winds is characterized by 24-36 hrs and 3-5 days (Perrone, 1979).

The speed of the Shamal wind ranges from 20 to 40 knots up to a peak of 50 knots (El-Sabh and Murty, 1989), and the wind blows against the inflowing currents at the Strait of Hormuz and induces a relatively large temporary change in the prevailing residual circulation (Sugden, 1963). The Shamal wind is a primary source of energy for mixing of Gulf waters and the waves produced by this wind move large amounts of water toward the southwest coast of the Gulf where there is significant dissipation of wave energy and mixing (Reynolds, 1993; Evans et al., 1973). Thoppil and Hogan (2010b) investigated the dynamic response of the Gulf to a winter Shamal forcing and used wind speed, wind stress vector, air temperature, humidity, precipitation, surface shortwave and long-wave heat fluxes that were predicted for a 4-5 days winter Shamal event to drive a numerical ocean model for the Gulf. They found that strong latent heat loss dominated surface heat loss due to the combined effect of decrease in specific humidity and strong winds, which enhanced evaporation, and the surface
heat loss induced significant sea surface temperature (SST) cooling. Furthermore, they also found an erosion of the thermocline due to strong mixing down the water column up to ~ 60m depths in the northwest regions of the Gulf. However, stratification within the Gulf remained stable in the southeast regions.

### 2.2.2 Evaporation

Despite the importance of the Gulf in international affairs, observation data on climatic and oceanic factors in the region are sparse. As Reynolds (1993) put it, "no other body of water of comparable size and economic importance is so under investigated as the Gulf." Estimates of net evaporation from the Gulf, which range from 1.4 m yr$^{-1}$ to 500 m yr$^{-1}$ are based on a few observational datasets and numerical modeling efforts. Using wet and dry bulb and sea surface temperature readings, Privett (1959) estimated a net evaporation \(^1\) rate of 1.44 m yr$^{-1}$, and Meshal and Hassan (1986) used data from the central Arabian coast to obtain a net evaporation rate of 2.02 m yr$^{-1}$. Ahmad and Sultan (1991) used meteorological observations to obtain an annual mean latent heat flux of 168 Wm$^{-2}$, which corresponds to a net evaporation rate of 2.12 m yr$^{-1}$. And recently, Johns et al. (2003) used hydrographic and current profile data obtained at the Strait of Hormuz to infer a net evaporation rate of 1.67 ± 0.39 m yr$^{-1}$, and Xue and Eltahir (2015) used a coupled regional atmosphere and Gulf numerical model to estimate a net evaporation rate of 1.84 m yr$^{-1}$.

Due to the excess of evaporation over precipitation, the Gulf contributes significantly to the world-wide evaporation minus precipitation (E-P) balance. Using an evaporation rate of 1.84 m yr$^{-1}$ and a surface area of $2.39 \times 10^5$ km$^2$, the yearly contribution of the Gulf toward the world-wide balance of E (runoff) is $4.4 \times 10^{11}$ m$^3$. And by comparison, the Red Sea, another system with an inverse estuary residual circulation with a surface area of $4.38 \times 10^5$ km$^2$, contributes $9.2 \times 10^{11}$ m$^3$ to the global balance of E-P (Nuemann, 1952).

\(^1\)Net evaporation implies that evaporation exceeds precipitation.
2.3 Physical Oceanography

2.3.1 Bathymetry

The Gulf is a shallow marginal sea with an average depth of \( \approx 35 \) m (Fig. 2-2). The depth increases from west, the Arabian coast, to east, the Persian coast, and reaches up to 100 m at the Strait of Hormuz, a narrow passage (\( \approx 56 \) m at its narrowest) that connects the Gulf to the Indian Ocean. There is no sill at the Strait of Hormuz (Sugden, 1963) and water depth increases sharply to > 3000 m in the Gulf of Oman and higher in the open ocean (Fig. 2-1). The shallowest region is the southwest shore that contains a variety of microenvironments, and Evans et al. (1973) grouped these environments into seven principal units: near-shore shelf, frontal reef, tidal deltas, frontal beaches and dunes, lagoonal channels, lagoonal terraces, and intertidal flats. Due to the shallowness of the west-southwest region compared to other parts of the Gulf, the impact of wind, evaporation and air temperature is strongest in these regions.

Figure 2-2: Depth profile of the Persian Gulf
2.3.2 Water Properties: Temperature & Salinity

The Gulf has the highest basin salinity of all oceanic basins because evaporation from the Gulf far exceeds the inflow of freshwater into the Gulf, but unlike the open ocean where temperature controls water density, salinity is a more important determinant of density in the Gulf (Sugden, 1963). Because the climate of the Gulf is continental with strong intra-annual variability in atmospheric climatic factors such as evaporation and air temperature, there is also strong intra-annual variability in water temperature and salinity. And due to the fact that no freshwater enters the shallowest west-southwest regions of the Gulf, atmospheric climatic factors have a stronger effect in these regions, thus the water temperature and salinities of the west-southwestern regions are the highest within the Gulf. However, the northern regions of the Gulf adjacent to the Tigris-Euphrates-Karun River Delta have the lowest temperatures and salinities due to the river runoff that enters the Gulf in these regions (Clarke and Keij, 1973).

Despite the importance of the Gulf as the source of seawater and sink of brine for desalination plants producing \(\approx 50\%\) of the world’s seawater desalination capacity and especially the importance of Gulf basin and regional salinities for planning, design and management of desalination plants, few direct measurements of water temperature and salinity at basin or regional scales can be found in peer reviewed literature. This scarcity of direct measurements is because the Gulf is shallow with a complex bathymetry, which makes sampling in space and time difficult, and moored instrumentation is even more difficult because of heavy marine traffic of up to one ship passing through the Strait of Hormuz every six minutes (Reynolds, 1993).

2.3.3 Residual Circulation

Residual circulation is the circulation that is left after subtraction of the periodic motion induced by tides. The residual circulation in the Gulf is due to three physical mechanisms (Hunter, 1983; Reynolds, 1993): wind forcing; positive buoyancy forcing (due to river discharge); and negative buoyancy forcing (due to evaporation). Sugden (1963), Hunter (1983), Nunes - Vas et al. (1990), Chao et al. (1992), and Reynolds (1993) have indicated that
the residual circulation in the Gulf is dominated by negative buoyancy forcing due to high rates of evaporation in the Gulf. Because of the arid climate where the Gulf is located, evaporation from the Gulf far exceeds freshwater inflow from precipitation and river runoff into the Gulf, and this creates an "inverse-estuary" like residual circulation in which water flows into the Gulf from the adjacent Indian Ocean in order to meet the water demand of (Fig. 1-4). Moreover, since evaporation only removes freshwater, the salt associated with the inflow from the ocean forms dense saltier water that sinks to the bottom of the Gulf and is removed as a bottom current from the Gulf to the Indian Ocean.

The restoring effect of the residual circulation is such that increase in Gulf water density, due to increase in salinity or decrease in temperature, leads to higher inflow into the Gulf from the Indian Ocean, and Indian Ocean water, which is less saline, then mixes with the denser Gulf water and thereby restores the density of the water in the Gulf. The residual circulation in the Gulf is three dimensional and complex, but the general impression is that the circulation forms a cyclonic gyre within the Gulf; the inflowing surface current, which enters along the Iranian coast, is broadest and reaches the northern parts of the Gulf in the summer, but in the winter, the lateral extent is substantially reduced and the longitudinal extent is only about half of that during the summer.

Exchange of mass (water and salt) and heat between the Gulf and the Indian Ocean occurs at the Strait of Hormuz (Figs. 2-1), a narrow passage that is about 56 km at its narrowest point. The Gulf deepens toward the Strait where the maximum depth approaches ~ 100 meters, and it has been shown that the dense saline water that sinks to the bottom of the Gulf due to evaporation flows out as dense bottom waters on the southern side of the Strait of Hormuz while the evaporated water in the Gulf is replenished with warm less dense waters from the Indian Ocean that enter the Gulf as surface inflow through the northern side of the strait (Sugden, 1963; Hunter, 1983; Chao et al., 1992; Reynolds, 1993). The orientation of the dense outflow and less dense inflowing waters is due to the Coriolis Effect, which deflects the inflowing water to the Persian Coast and the outflowing waters to the Arabian Coast.

Flushing time is the time required for all the water in the Gulf to be exchanged with water from the open ocean, and flushing time depends on the strength of the evaporation-
driven residual circulation that controls the longitudinal exchange of water. The removal of salt and pollutants from the Gulf depends on the flushing time; a short flushing time indicates that pollutants will be removed more quickly from the Gulf, whereas accumulation of pollutants may occur for long flushing times. Hunter (1983) reports flushing time estimates of 2 - 5.5 years for the Gulf that were obtained using the evaporation rate in the Gulf and conservation of water and salt considerations. More recently, Xue and Eltahir (2015) used a coupled Gulf-atmosphere numerical model to estimate a flushing time of 14 months for the Gulf.

2.4 Seawater Desalination

Because of large urban population (Table 1.1), arid climate and very little groundwater resources, the Gulf is the source of seawater and sink of brine discharge for desalination plants producing ≈50% of the world’s seawater desalination capacity, and more than 850 seawater desalination plants of various capacities are currently online or under construction in the Gulf 2-3. All the water supplies of Kuwait, Bahrain, UAE and Qatar, and about half of the water supplies of UAE and Saudi Arabia are obtained from seawater desalination (Walgate, 1978; Purnama et al., 2005; Lattemann and Hopner, 2008). It is useful to compare the amount of water that is removed from the Gulf by evaporation and seawater desalination as a first step in understanding the impact of these processes on the Gulf. Using the data in Fig. 2-3, the annual rate of water withdrawal for desalination in the Gulf ($D_{aw}$) is

$$D_{aw} = 11,786,494 \text{ m}^3/\text{day} \times 365 \text{ days} = 4.3 \text{ billion m}^3$$

Similarly, using recently obtained evaporation estimates (Xue and Eltahir, 2015), the annual amount of water lost to evaporation ($E_{aw}$) is

$$E_{aw} = 1.84 \text{ m/yr} \times 2.39 \times 10^{11} \text{ m}^2 = 439.8 \text{ billion m}^3$$

and comparison of Eq. 2.1 and 2.2 shows that annual water withdrawal for desalination is ~ 1% of water lost to evaporation.
However, a major impact of seawater desalination in the region is the disposal of brine, the hot and highly saline (up to $1.5 \times$ ambient salinity) effluent from desalination plants that contains several other chemicals, into the Gulf (Purnama et al., 2005). Haphazard disposal of brine into the Gulf may have considerable adverse effects (Dabbagh et al., 1993), especially on the density-driven residual circulation since brine discharge into the Gulf introduces non-uniform buoyancy forcing, but the system is driven by uniformly distributed buoyancy forcing (evaporation). Sheppard et al. (2010) have highlighted the absence of a regional cooperative and systematic approach for seawater desalination and discharge of brine into the Gulf as a major concern for the stability of the Gulf system.

From an ecological perspective, disposal of brine into the Gulf may alter limiting environmental parameters, and hence, may threaten the survival of flora and fauna in the Gulf.
system. There are five critical limits of tolerance for any limiting environmental parameter: maximum limit for survival; maximum limit for successful reproduction; optimum; minimum limit for successful reproduction, and minimum limit for survival (Evans et al., 1973). And changes in any one of these limits may have a significant impact on the ecological viability of the Gulf system.
Chapter 3

Equilibrium Properties of the Gulf

3.1 Introduction

The possibility that the climate system may be sensitive to initial conditions or exhibit multiple equilibria is of practical and theoretical importance because equilibrium properties of climate are the basis for characterizing the past, and hence the key to quantitative estimation of climate change due to human activities (Ferreira et al., 2010; Ashkenazy et al., 2012; Stocker, 1999; Lorenz, 1970, 1968; Stommel, 1961). Resilience of the climate system to perturbations is strongly affected by multiple equilibrium states, since perturbations exceeding the thresholds separating domains of different equilibria would be enhanced by natural feedbacks, and those below such thresholds would be naturally restored back to the original equilibrium. Equilibrium properties of coastal ocean basins are of greater socioeconomic importance because these systems are essential to fisheries, water supply, and marine transport (Stommel, 1951; Iselin, 1940). However, in addition to the complexity of adequate sampling in space and time, heavy marine traffic also makes it difficult to sample and determine equilibrium properties in coastal ocean basins.

The existence of multiple climate equilibria is one of the most central theoretical questions of climate science. Oceanic and atmospheric studies have shown models that exhibit multiple equilibria on both global and regional scales. For example, using a simple energy balance model (EBM) or more comprehensive coupled ocean-atmosphere-sea ice general circulation model (GCM), multiple equilibria, with three different stable states, were found for the
same set of parameters and external forcing including 1) a state in which a polar sea ice cap extends into the mid-latitudes, 2) an ice-free warm state, and 3) a completely sea ice-covered "snowball" state (Budyko, 1969; Sellers, 1969; Langen and Alexeev, 2004; Ferreira et al., 2010). And the factors responsible for multiple equilibria in these models are feedbacks related to changes in the oceanic overturning circulation, ice-albedo effects and radiative-convective properties of the atmosphere.

Bio-geophysical feedbacks between vegetation and climate can also lead to multiple equilibria in the biosphere-atmosphere system and are reported to possibly induce abrupt regime shifts in climate. Several modeling studies show that vegetation-climate feedbacks at regional scales could be sufficiently strong to establish multiple equilibria states in the regional climate system through modification of surface albedo, evapotranspiration, and surface roughness. Other studies use simulated multiple equilibria and desertification thresholds to explain regime shifts of vegetation on multi-decadal time scales in West Africa (Claussen and Esch, 1994; Brovkin et al., 1998; Wang and Eltahir, 2000; Zeng and Neelin, 2000; Dekker et al., 2010; Bathiany et al., 2012).

A recently developed high-resolution two-way coupled Gulf-Atmosphere Regional Model (GARM) that is forced by solar radiation and constrained by observed lateral boundary conditions (Xue and Eltahir, 2015) is used in this study to investigate the equilibrium properties of the Gulf. And the climate of the Gulf system is simulated assuming different initial conditions for a ten-year time period because this time period is sufficient to characterize Gulf climate system since the average flushing time of the Gulf is a few years (Sadrinasab and Kampf, 2004; Xue and Eltahir, 2015).

3.2 Observation Data

3.2.1 SST

Because the Gulf is shallow, Gulf sea surface temperature (SST) and Gulf basin temperature have a correlation coefficient of 98%. The SST data used in this study to validate Gulf SST simulated in GARM is the NOAA 1/4° daily Optimum Interpolation Sea Surface
Temperature (or daily OISST), which is an analysis constructed by combining observations from different platforms (satellites-AVHRR, ships, buoys) on a regular global grid, and the spatially complete OISST map is produced by interpolating to fill in gaps. The methodology for producing the SST data also includes a bias adjustment of satellite and ship observations (referenced to buoys) in order to compensate for platform differences and sensor biases (Reynolds et al., 2007). The basic daily OISST methodology is described in Reynolds et al. (2007), and OISST- AVHRR has been validated at regional and global scales (Boehme et al., 2014; Saha et al., 117) and used to investigate temporal variability at the regional scale (Krishnamurthy and Kirtman, 2009; Stramska, 2015).

3.2.2 Salinity

Observations of the water properties, especially salinity, in the Gulf are limited in spatiotemporal coverage and there are few published basin-wide survey results including a 1948 summer cruise (Emery, 1956), the 1976 wintertime expedition of the Atlantis from Woods Hole Oceanographic Institution (Brewer and Dryssen, 1985), and the surveys from February to June 1992 on the Mt. Mitchell expedition (Reynolds, 1993). An historical observational hydrographic dataset was compiled by Swift and Bower (2003), based primarily on the Master Oceanographic Observations Data Set (MOODS) maintained by the U.S. Naval Oceanographic Office, in order to describe the seasonal variability of the water properties in the Gulf. And the U.S. Navy data includes both bottle casts and conductivity and temperature measuring data at 1758 stations that cover most of the Gulf, but the data also has large temporal gaps and a bias toward winter and spring months (Swift and Bower, 2003). For example, the water properties from September to December are significantly under sampled and less than 100 casts are recorded/available. Moreover, most historical hydrographic samplings were made during the 60s and 90s and very limited samplings were made in between or post 2000.

The Strait of Hormuz, which connects the Gulf to the Indian Ocean, and surrounding regions are also poorly sampled spatially, although there are some measurements of the water exchange at the strait that consisted of a mooring site in the deep channel at the strait and four seasonal transects across the strait. But no stations are located within the shallow
bays and basins along the Arabian coast, and only a few stations, collected in March 1977 and the 1990s, are located within the topographic bank of the Gulf (Johns et al., 2003). The Mt. Mitchell surveys in winter (late February-early March) and spring (late May-early June) of 1992 remain the most comprehensive CTD sampling that covered many regions of the Gulf that were poorly sampled by other expeditions including the Strait of Hormuz and the shallow southern banks (Reynolds, 1993).

3.2.3 Water Surface Elevation

The altimetry data used in this work are the satellite derived gridded (0.25°×0.25°) delayed time daily absolute dynamic topography (ADT) from the Ocean Surface Topography Mission (OSTM) TOPEX/Poseidon, Jason-1 and Jason-2 satellite altimetric mission. ADT is the sum of sea level anomaly (SLA) and mean dynamic topography (MDT), which are both referenced over a twenty-year period. ADT is produced by the Data Unification and Altimeter Combination System (SSALTO/DUACS) and distributed by Archiving, Validation and Interpretation of Satellite Oceanographic data (AVISO), with support from Centre National D’Etudes Spatiales (CNES). DUACS applies the standard geophysical and atmospheric corrections (tides, wet and dry tropospheric corrections, ionospheric correction, sea state bias, and instrumental drifts and bias) to the satellite measurements. TOPEX/POSEIDON satellite, launched on 10 August 1992 and decommissioned on 18 January 2006, has a vertical resolution of 4.2 cm; Jason-1 satellite, launched on 7 December 2001 and decommissioned on 21 June 2013, has a vertical resolution of 4.2 cm; and Jason-2 satellite, launched on 20 June 2008, has an improved globally averaged vertical resolution of 3.4 cm (Tab. 3.1) (TOPEX/POSEIDON Handbook, 1996; Jason-1 Handbook, 2015; Jason-2 Handbook, 2011).

An important design goal for multi-mission ocean surface topography satellites is to measure the ocean topography to the same performance level in order to provide an extended continuous time series of high-accuracy measurements of ocean topography that is suitable for both basin and global investigations (Bosch et al., 2014). Introducing SOL [m] for a Static Ocean Level (geoid: equipotential surface of the combined gravitational and centrifugal force fields of the earth), and R [m] for the measured distance between a satellite and the ocean.
Table 3.1: Ocean altimetry satellites; the derived variable is the absolute dynamic topography (ADT) at the corresponding horizontal and vertical resolution (horlz and vrt. res) and for the corresponding operation period.

<table>
<thead>
<tr>
<th>Satellites</th>
<th>TOPEX</th>
<th>Jason-1</th>
<th>Jason-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Derived variable</td>
<td>ADT</td>
<td>ADT</td>
<td>ADT</td>
</tr>
<tr>
<td>Horiz. res.</td>
<td>0.25°×0.25°</td>
<td>0.25°×0.25°</td>
<td>0.25°×0.25°</td>
</tr>
<tr>
<td>Vert. res</td>
<td>4.2cm</td>
<td>4.2cm</td>
<td>3.4cm</td>
</tr>
<tr>
<td>Operation period</td>
<td>Aug 92 - Jan 06</td>
<td>Dec 01 - Jan 13</td>
<td>Jun 08 -</td>
</tr>
</tbody>
</table>

surface, the ADT [m] may be decomposed in two ways:

\[ ADT = R - SOL \]  \hspace{1cm} (3.1)

\[ ADT = MDT - SLA \]  \hspace{1cm} (3.2a)

\[ SLA = SLA_{STERIC} - SLA_{MASS} \]  \hspace{1cm} (3.2b)

\( SLA_{STERIC} \) is the sea level anomaly due to changes in density resulting from changes in temperature and salinity, both of which can be estimated by direct measurement, while \( SLA_{MASS} \) is due to changes in mass, from interaction of the ocean with the atmosphere and continents, which may be inferred from satellite gravimetry measurements. \( SLA \) can also be estimated from wave height measurements such as tidal gauges. These external independent sources of measurement for the components of ADT have provided a means to check the accuracy of satellite measured ADT, and are therefore a mechanism for improving the geophysical and atmospheric corrections applied to the ADT (Garcia et al., 2007; Wei and Min, 2015; Cheng and Qi, 2010; Valladeau et al., 2012; Ruiz-Etcheverry et al., 2015; Shanas et al., 2014; Ivchenko et al., 2007). Moreover, ADT provides a means (Eq. 3.2a) to estimate basin scale temperature and salinity, especially in shallow regions, where pressure (depth) plays a secondary role in the variability of density.

Continuous time series of AVISO multi-mission satellite measured altimetry is a relatively young research dataset (≈23 years), and due to the importance of validating these time measurements with external independent sources of ocean altimetry in order to make
them suitable for global and regional climate research (Ablain et al., 2015), research efforts, especially at the regional scale, have been limited by the availability of other independent measurements of ocean altimetry. AVISO altimetry datasets have been used for several regional investigation, including trends in basin-scale features of the world’s major oceans (Fang and Zhang, 2015), and sea level change and variability in the central Indian Ocean, Mediterranean Sea, South China Sea, and South American continental shelf (Dunne et al., 2012; Casanave et al., 2001; Zhuang et al., 2010; Saraceno et al., 2014). AVISO altimetry datasets have also been used to investigate variability of salinity in the western, tropical and equatorial Pacific Ocean (Maes and Behringer, 2000; Vossepoel et al., 1999, 2002).

### 3.3 Equilibrium Experiments

#### 3.3.1 Gulf-Atmosphere Regional Model (GARM)

The primary tool for the investigations reported in this work (Fig. 3-1) is a two-way coupled Gulf-Atmosphere Regional Model (GARM) (Xue and Eltahir, 2015). The hydrodynamic model of GARM was developed using unstructured-grid Finite Volume Community Ocean Model (FVCOM) (Chen et al., 2003), which has been used widely to investigate estuaries and coastal oceans because its unstructured grid is ideal for geometrical fitting (Chen et al., 2003, 2006). FVCOM solves the momentum and thermodynamic equations using a second order finite-volume flux scheme that ensures mass conservation in individual control volumes and the entire computational domain (Chen et al., 2006). The horizontal resolution of the Gulf in FVCOM is 3km near the coast, 5km in offshore regions and 10-15km near the open boundary with the Indian Ocean. FVCOM is configured with a realistic bathymetry of the Gulf, and because the Gulf is shallow (mean depth ≈35m), the vertical coordinate in FVCOM is configured with thirty generalized sigma layers in order to have <1m vertical resolution in near shore areas (< 60m in depth) and 1-2m in most offshore (> 60m in depth) areas.

The atmospheric model of GARM, MIT Regional Climate Model (MRCM), is an advanced version of the Regional Climate Model version 3 [RegCM3] (giorgi and Mearns, 1999;
Gulf-Atmosphere Regional Model (GARM)

MIT Regional Climate Model (MRCM)
Rectilinear grid
118 x 118 x 18 (30km)

Atmosphere -to- Ocean
Wind stress
Evaporation-precipitation flux
Heat fluxes

Finite Volume Community Ocean Model (FVCOM)
Unstructured grid

Ocean -to- atmosphere
Sea surface temperature (SST)

16607 Nodes
31616 Elements
30 Sigma layers
2-3 km near coasts
5km in offshore regions
10-15km @open boundary

Figure 3-1: Gulf-Atmosphere Regional Model (GARM); the atmosphere component is the MIT Regional Climate Model (MRCM) and the ocean component is the Finite volume Community Ocean Model (FVCOM).

Pal et al., 2007). MRCM has the skill to simulate the climate of different regions because MRCM has new physical schemes, or modified versions of the original schemes in RegCM3 including coupling of MRCM with IBIS land surface scheme (Winter et al., 2009), new convective cloud scheme (Gianotti and Eltahir, 014a), new convective rainfall autoconversion scheme (Gianotti and Eltahir, 014b), modified boundary layer height and boundary layer cloud scheme (Gianotti, 2013), new surface albedo assignment (Marcella and Eltahir, 2012) and new irrigation scheme (Marcella and Eltahir, 2014). MRCM is configured with a rectilinear grid (118 x 118 x 18) with 30km horizontal resolution in order to simulate the climate of the Gulf, but the domain of MRCM (29E - 61E longitude and 12N - 40.5N latitude) is
larger than the domain of FVCOM because of the different spatial scales of atmospheric and Gulf circulations. MRCM uses Zeng's bulk aerodynamic ocean flux parametrization scheme (Zeng et al., 1998) to parametrize the SST fields provided by FVCOM.

FVCOM and MRCM are coupled in GARM using the OASIS3 software, which implements end-to-end coupling of different numerical models in a parallelized environment (Valcke, 2013). FVCOM and MRCM are integrated forward simultaneously and the coupling fields at the atmosphere-ocean interface are calculated in each model, then OASIS3 interpolates and transfers the coupling fields of different resolution from the source grid to the target grid at a coupling frequency of 3 hours: atmospheric wind stress, evaporation-precipitation flux, and heat fluxes (incoming solar radiation, net surface longwave radiation, latent and sensible heat) are transferred by OASIS3 from MRCM to FVCOM, and sea surface temperature (SST) is transferred by OASIS3 from FVCOM to MRCM (Xue and Eltahir, 2015). OASIS3 has been used to couple FVCOM and RegCM3 (the precursor of MRCM) over the Maritime Continent (MC) and this coupled model simulates realistic decadal climatologies of the MC region including the South China Sea and Indonesian Archipelagoes (Wei et al., 2014). OASIS has also been used to couple FVCOM and MRCM over the MC and numerical experiments in this coupled model system identified a local-scale negative feedback process that restores SST perturbations and dominates local-scale air-sea feedback mechanisms over the shallow shelf water region (<200m) of the MC (Xue et al., 2014).

3.3.2 Experimental Design

Six experiments were performed in GARM under identical ocean and atmosphere boundary conditions but starting from six different initial conditions (Tab. 3.2). All experiments were started with a uniform initial salinity and temperature condition in the entire Gulf except for the control simulation (Ic1) where spatial variability in the initial conditions is imposed. Climatological monthly mean fields of temperature (Locarini, 2010) and salinity (Antonov, 2010) from the World Ocean Atlas 2009 that consist of 1° objectively analyzed climatological fields of in-situ temperature and salinity at standard depth levels for seasonal periods are applied to the open ocean boundary conditions in the hydrodynamic component (FVCOM) of GARM in all experiments. This boundary temperature and salinity data is used with wind
Table 3.2: Initial salinity and temperature for all experiments. All equilibrium experiments, except Ic1, were started with a constant salinity and temperature. Ic1 was started with spatially variable initial salinity with mean 40.1 g/kg, and spatially variable temperature with mean 21.4°C.

<table>
<thead>
<tr>
<th>Decadal Experiments</th>
<th>Initial Salinity (g/kg)</th>
<th>Initial Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ic1</td>
<td>Spatially variable (Mean=40.1)</td>
<td>Spatially variable (Mean=21.4)</td>
</tr>
<tr>
<td>Ic2</td>
<td>24.8</td>
<td>24.8</td>
</tr>
<tr>
<td>Ic3</td>
<td>42.6</td>
<td>24.8</td>
</tr>
<tr>
<td>Ic4</td>
<td>38.0</td>
<td>24.8</td>
</tr>
<tr>
<td>Ic5</td>
<td>39.0</td>
<td>24.8</td>
</tr>
<tr>
<td>Ic6</td>
<td>40.0</td>
<td>24.8</td>
</tr>
</tbody>
</table>

forcing data from the atmosphere component (MRCM) of GARM to dynamically calculate the mean flow velocity that resolves the wind-driven and buoyancy-driven flow at the open ocean boundary in the Indian Ocean. Tidal forcing is excluded from all experiments because tides do not make an important contribution to the mean circulation in the Gulf (Reynolds, 1993; Thoppil and Hogan, 2010a).

The three main sources of freshwater into the Gulf are the Tigris, Euphrates and Karun Rivers that enters the Gulf at the Tigris-Euphrates-Karun River Delta (Emery, 1956; Reynolds, 1993). Since the objective of this study is to simulate the climate of the Gulf, climatological monthly mean rates of river inflow at the confluence of these three rivers, with an annual mean flow of 1576 m$^3$s$^{-1}$ and high flow seasons between March and May, are used for the freshwater boundary condition in FVCOM (Saleh, 2010; Xue and Eltahir, 2015). MRCM provides surface forcing (wind, precipitation, evaporation, shortwave and longwave radiation, and latent and sensible heat fluxes) to FVCOM, and the atmospheric boundary conditions for MRCM were obtained from the current climate (1981 - 1990) simulations of ECHAM5/MPIOM (Max Planck Institute Ocean Model) climate model of the Max Planck Institute for Meteorology (now renamed as Max Plank Institute Earth System Model (MPI-ESM) in the latest Coupled Models Intercomparison Project Phase 5). The choice of MPI-ESM to provide atmospheric boundary conditions for MRCM is because future research to extend this work may include projection of the impact of future climate on the Gulf and only global general circulation models can provide the atmospheric boundary conditions for
future climate. Moreover, MPI-ESM is considered one of the better global climate models, and sensitivity experiments in GARM that compared boundary conditions obtained from climate simulations of MPI-ESM and boundary conditions obtained from observed climate data showed similar results (Xue and Eltahir, 2015).

3.4 Results

3.4.1 Multiple Salinity Equilibria

Evaporation (Fig. 3-2) over the Gulf [\(\approx 1.84 \text{m/yr}\)] is much larger than freshwater input from precipitation [\(\approx 0.07 \text{m/yr}\)] (Fig. 3-3) and river runoff [\(\approx 0.21 \text{m/yr}\)] (Fig. 3-4), and this deficit (1.62 m/yr) is met by lateral inflow of water from the adjacent Indian Ocean through the Strait of Hormuz (Reynolds, 1993; Xue and Eltahir, 2015). Since evaporation only removes freshwater, enabling the residual circulation to replenish the Gulf with saline water through the Strait of Hormuz, the salt associated with this added saline water must be returned to the ocean in order to maintain equilibrium salt conditions. Starting from different initial
Figure 3-3: Seasonal precipitation into the Gulf simulated in GARM.

Figure 3-4: Seasonal river inflow into the Gulf.
conditions, two distinct equilibria were found for the Gulf: first, a low-salinity equilibrium (Ic2) in which water from the ocean enters the Gulf through the bottom of the strait and the Gulf outflow exits through the surface of the strait into the ocean (estuary circulation) (Fig. 3-5 and Fig. 3-6); and second, a high-salinity equilibrium (Ic1), but in this case the circulation is reversed with water from the ocean entering the Gulf at the surface through the strait and the Gulf outflow exiting through the bottom of the strait into the Indian Ocean (inverse-estuary circulation).

The surface temperature (Fig. 3-7) during winter and summer in both the high and low salinity equilibria are similar, but the seasonal variability of basin temperature (Fig. 3-5) plays an important role in differentiating the circulations between the Gulf and the Indian Ocean that are associated with the two equilibria. Gulf seasonal minimum and maximum water density in the two equilibria varies over a range of ≈3kg/m³ due to the large difference between the seasonal minimum and maximum basin temperature (≈13°C). When Gulf water is heavier than Indian Ocean water, due to the higher density of Gulf water such as in Ic1 equilibrium, the circulation between the Gulf and the Indian Ocean is counterclockwise because Gulf water sinks and exits the Gulf in bottom layers while Indian Ocean water floats and enters the Gulf in top layers. But when Gulf water is lighter than Indian Ocean water, due to the lower density of Gulf water such as in Ic2 equilibrium, the circulation between the Gulf and the Indian Ocean is clockwise because Gulf water floats and exits the Gulf in top layers while Indian Ocean water enters the Gulf in bottom layers.

The density and water level of the Gulf decreases and increases respectively relative to the Indian Ocean as the Gulf warms from winter to summer in Ic2, and consequently, the clockwise circulation between the Gulf and the Indian Ocean in Ic2 equilibrium is enhanced from winter to summer and diminished from summer to winter. However, the density and water level of the Gulf increases and decreases respectively relative to the ocean as the Gulf cools from summer to winter in Ic1 equilibrium, and therefore, the counterclockwise circulation between the Gulf and the Indian Ocean is enhanced from summer to winter and diminished from winter to summer.

Simulation with Ic2 has an estuary flow pattern, so-called “salt wedge” that depends on

\[1\text{ in a vertical cross section with the observer facing northbound} \]
Figure 3-5: Equilibrium basin salinity (a) and temperature (b) for the low salinity equilibrium (Ic2) and high salinity equilibrium (Ic1) compared with observation. Ic1 SST is correlated with the basin temperature with an R value of 0.98, while Ic2 SST and the basin temperature are correlated with an R value of 0.94.

the balance of baroclinic forcing and mixing effects. Fresh water float on top of seawater in a layer that gradually thins seaward, while denser seawater at the bottom forms a wedge-shaped layer that thins landward. In contrast, the simulation with Ic1 represents an inverse
Figure 3-6: Net mass flux / total surface area of the Strait of Hormuz (difference between the mass flux into the Gulf from the ocean and the mass flux out of the Gulf into the ocean) during winter and summer for Ic1& Ic2. The deepest parts of the Strait are near the Arabian Coast while the shallow parts of the Strait are near the Persian Coast.

An estuary such as the present state of the Gulf, which occurs in arid climates where evaporation greatly exceeds the inflow of freshwater and this causes seawater to flow landward from the upper layer in order to balance the freshwater loss. The more saline and denser flow exits the Gulf through the bottom and the salt associated with the inflowing seawater is removed in outflowing dense saltier water.

The densest water that flows out of the Gulf, which forms in winter at the northern end
of the Gulf, mixes across a density front that separates Gulf deep water from the Indian Ocean Surface Water (IOSW). The IOSW enters the Gulf in two branches, one along the Iranian coast toward the northern Gulf and the other along the southern banks. The primary horizontal circulation pattern within the Gulf is a cyclonic gyre with the inflow of ocean water entering mainly through the northern part of the strait and forming a cyclonic circulation gyre returning to the southern Gulf. The northern Gulf can also maintain a smaller cyclonic circulation, and there are southward coastal currents, between the head of the Gulf and
Figure 3-8: Equilibrium basin salinity (a) of all experiments (Ic1, Ic2, Ic3, Ic4, Ic5, Ic6), seasonal equilibrium salinity of all experiments (b); the basin salinity for the three intermediate equilibria (Ic4, Ic5, Ic6) are bounded below by the salinity of Ic2 (low salinity equilibrium) and above by the salinity of Ic1 (high salinity equilibrium). Ic3 experiment, started with salinity higher than the high salinity equilibrium, is restored back to the high salinity equilibrium (Ic1).
Figure 3-9: Equilibrium surface salinity of the low salinity equilibrium (Ic2) and the high salinity equilibrium (Ic) compared with observed salinity (Reynolds, 1993).

Qatar, that extend to the east of Qatar and north of United Arab Emirates with an outflow through the southern part of the strait. The seasonal variation of flow in and out of the Gulf is controlled by changes in Gulf surface slope, due to variation in evaporation rate, and the difference between the density of Gulf water in the interior of the basin and water at comparable depths in the adjacent ocean (Reynolds, 1993).

The stability of Ic2 and Ic1 were investigated and three intermediate equilibria were found in the space between the salinity of Ic2 and Ic1 (Fig. 3-8), but the circulation associated with these three equilibria, bottom inflow into the Gulf from the ocean in late summer and
bottom outflow from the Gulf into the ocean in winter, are a mixture of the circulations of Ic2 and Ic1. These three equilibria are important in shaping the resilience of the Gulf system to human activity. A decrease in Gulf water density, from natural variability or human activities, will move the system toward Ic2, and an increase in Gulf water density will move the system toward Ic1. A sensitivity experiment initializing GARM with salinity higher than Ic1 shows that the Gulf may be insensitive to increases in salinity beyond the salinity of Ic1 (Fig. 3-8) because of the inverse estuary circulation. An increase in basin salinity will increase the Gulf water density, and hence increase the pressure-gradient force between the Gulf and the ocean. And, since the stronger circulation that results from the increased pressure-gradient force brings more ocean water to mix the Gulf water and removes more dense saline water from the Gulf to the ocean, the pressure-gradient force weakens and the basin salinity is restored back to the salinity of Ic1.

3.4.2 Estimate of Basin Salinity

The rapid growth of desalination in the Gulf has renewed the urgency for an estimate of the basin salinity, which has been difficult to obtain due to scarcity of observation data, and the most comprehensive surface salinity data from a 1992 expedition is limited in spatiotemporal coverage (Reynolds, 1993) (Fig. 3-9). Instead, satellite altimetry data is used in this study to constrain the simulated water surface elevation (Fig. 3-10) in order to provide an estimate of Gulf basin salinity. Satellite altimetry data measures the water surface elevation in the Gulf, which is a function of the prevailing basin temperature and basin salinity, and GARM simulates the water surface elevation in the Gulf for the different equilibria. Since the simulated basin temperature distribution is similar in Ic2 and Ic1 (Fig. 3-5), the prevailing basin salinity is inferred by comparing the observed and simulated water surface elevation, and we estimate the basin salinity to be in the range 40.5 - 41g/kg, which corresponds to the salinity of Ic1.

Desalination in the Gulf, which already amounts to about half of the world’s desalination capacity, is projected to be the source of forty percent of the 200km³ water deficit in the region by 2050. The results presented here suggest that, under the current ocean boundary conditions, the current basin salinity of the Gulf may be insensitive to desalination activities.
Figure 3-10: Equilibrium water surface elevation for low salinity equilibrium (Ic2) and high salinity equilibrium (Ic1) compared with remotely sensed water surface elevation (Jason I-II satellite); the satellites have an accuracy of 2.5 - 3.4 cm. The water surface elevations of the three intermediate equilibria (not shown here), like their salinities, are also bounded between the water surface elevations of Ic1 & Ic2.

due to the restoring effect of the inverse estuary circulation. However, desalination may change the dynamics of the internal circulation within the Gulf, and regional dynamics within the Gulf may in fact be sensitive to the hypersaline brine discharge from desalination plants.

### 3.5 Water Balance Under Multiple Salinity Equilibria

The multiple equilibria in the Gulf, distinguished by water surface elevation and salinity, may be derived from the water balance of the Gulf, which consists of hydrometeorologic components (precipitation, evaporation, river runoff (Fig. 3-3, 3-2, 3-4)) and barotropic and baroclinic flow components: surface elevation-driven transport into the Gulf from the Indian Ocean (IO) and density-driven transport from the Gulf to the IO. Introducing \( W_G \) [m] for water surface elevation of the Gulf, \( T \) [yr] for time period, \( P \) [m/yr] for precipitation into the Gulf, \( E \) [m/yr] for evaporation from the Gulf, \( R \) [m/yr] for river runoff into the Gulf,
Figure 3-11: Scatter plot of advection \( (Adv) \) of water into the Gulf as a function of Gulf water elevation, both of which are derived from the numerical model (GARM); the best fit quadratic curve has an \( R^2 \) value of 43%. This equation of the quadratic fit is equivalent to Eq. 2.

\[ Adv [\text{m/yr}] \] for the surface elevation gradient-driven transport into the Gulf from the Indian Ocean (IO), and \( Conv [\text{m/yr}] \) for the density-driven transport from the Gulf to the IO, the water balance of the Gulf can be written as:

\[
\frac{\partial W_G}{\partial T} = P + R - E + Adv + Conv
\]  

(3.3)

where \( Adv \) is driven by the surface elevation gradient between the Gulf and the ocean, and hence, a function of the difference between the water surface elevations of the Gulf \( W_G \) and the IO \( W_O \). \( Conv \) is a function of the difference in the density of the Gulf \( \rho_G \) and the IO \( \rho_O \). Let \( \Delta W = W_O - W_G \), and \( \Delta \rho = \rho_G - \rho_O \) so that:

\[
Adv = f_a(\Delta W)
\]  

(3.4)

\[
Conv = f_c(\Delta \rho)
\]  

(3.5)
Figure 3-12: Scatter plot of convection (Conv) of water out of the Gulf as a function of the difference of Gulf and Indian Ocean (IO) density; the density of the Gulf and convection of water from the Gulf to the IO are derived from the numerical model (GARM), and the density of the IO is assumed constant. The best fit quadratic relationship has an R² value of 62%, and this relationship is equivalent to Eq. 3.

Owing to the spatial scale of the ocean relative to the Gulf, $W_O$ and $\rho_O$ may be assumed constant at the annual time scale, and because the Gulf is shallow (mean depth $\approx 35$ m), the density of the Gulf, which varies between 1026.5 - 1029.5 kg/m³, may be assumed to be a function of the temperature ($T_G$) and salinity ($S_G$) of the Gulf, that is, $\rho_G(T_G, S_G)$. Therefore, given a seasonal distribution of Gulf temperature $T_G$ (Fig. 3-5), equilibrium conditions at the annual time scale, with corresponding pairs of $W_G$ and $S_G$, can be derived under the condition that the sum of intra-annual variations of $W_G$ vanishes, that is

$$\sum_{i=1}^{N=1yr} \frac{dW_G}{dT} = \sum_{i=1}^{N=1yr} P + R - E + f_a(W_G) + f_e(S_G) = 0 \quad (3.6)$$

$f_a$ and $f_e$ (Eq. 3.4, Eq. 3.5) are both derived from GARM (Fig. 3-11, 3-12) and used according to Eq. 3.6 to derive a salinity vs. water elevation contour space (Fig. 3-13). The contour values are normalized by the annual lateral inflow rate (33.7 m/yr). And the small deviations of the equilibria simulated in GARM from the zero-contour line indicate that the
Figure 3-13: Illustration of Gulf multiple salinity equilibria and the mean water surface elevation corresponding to each equilibrium salinity. Contour values are computed at the annual time scale using Eq. 4, and normalized by the annual advection rate (33.7 m/yr). Hence, contour values are unitless and represent fractions of annual water advected into the Gulf from the Indian Ocean. The pair of equilibrium salinity and mean water elevation for the six experiments (lc1, lc2, lc3, lc4, lc5, lc6) performed in GARM are plotted in colored dots.

total error in the values of evaporation, precipitation, river and inflow and outflow, used in Eq. 3.6, have minimal effect on the accuracy. The deviation of the equilibrium salinity and mean water elevation simulated in GARM (lc1, lc2, lc3, lc4, lc5, lc6) from the zero-contour line can be attributed first to the accuracy of the quadratic fit of the advection and convection functions. Secondly, the deviations are also due to assumptions in the derivation of Eq. 5 including constant salinity and temperature of the Indian Ocean, and zero variability in Gulf salinity at the intra-annual time scale.
Chapter 4

Transition between Salinity Equilibria in the Gulf

4.1 Introduction

The multiple salinity equilibria in the Gulf can be described by an equilibrium landscape divided into three regions Fig. 4-1: the first region corresponds to the low salinity equilibrium, the second region corresponds to an infinite number of intermediate salinity equilibria, and the last region corresponds to the high salinity equilibrium. The three intermediate equilibria (Ic4, Ic5 and Ic6) simulated in GARM and shown here (Fig. 3-8) are representative of the infinite number of possible intermediate salinity equilibria in the second region of the equilibrium landscape.

The circulation between the Gulf and the Indian Ocean (Fig. 3-6) associated with the low salinity equilibrium (Ic2), surface inflow and bottom outflow in the winter and surface outflow and bottom inflow in the summer, can be classified kinematically as an oscillation with finite angular displacement; like a simple pendulum that oscillates around its lowest point, the point of suspension. The lateral inflow and outflow between the Gulf and the ocean in Ic2 equilibrium each have two velocity extrema: the first maximum inflow and outflow velocities occur during the counterclockwise winter circulation and the second maximum inflow and outflow velocities occurs during the clockwise summer circulation (Fig. 4-2). This is analogous to the two velocity extrema at the point of suspension in an oscillating
Simple pendulum. The first (February) maximum inflow and outflow velocities in late winter occur when Gulf water surface elevation is lowest (Fig. 3-10) and Gulf density is highest (Fig. A-10) relative to the water surface elevation and density of the ocean respectively; thus, gravity drives surface inflow to the Gulf from the ocean and pressure gradient force drives bottom outflow from the Gulf to the ocean. The second (October) maximum outflow and inflow velocities in late summer occur when the Gulf water surface elevation is highest and Gulf density is lowest relative to the water surface elevation and density of the ocean respectively; thus, gravity drives surface water outflow from the Gulf to the ocean and pressure gradient force drives bottom water inflow to the Gulf from the ocean.

In contrast, the circulation between the Gulf and the Indian Ocean (Fig. 3-6) associated with the high salinity equilibrium (Ic1), surface inflow and bottom outflow that are strongest in winter and weakest in summer, can be classified kinematically as a counterclockwise rotation with infinite angular displacement; like a simple pendulum with high velocity such that the pendulum always rotates counterclockwise around its center of suspension. The lateral inflow and outflow velocities between the Gulf and the ocean in Ic1 equilibrium have maxima in February and minima in October (Fig. 4-2); analogous to the maximum and minimum velocities at the times when a simple pendulum that always rotates counterclockwise reaches the 270° (downward axis) and 90° (upward axis) points respectively in a vertical circle. Because Gulf water surface elevation and density (due to high salinity) is always lower and higher respectively than the water surface elevation and density of the ocean (Fig. 3-10 and Fig. A-10), there is no change in the direction of the forces that drive surface inflow.
into the Gulf and bottom outflow from the Gulf throughout the year. But, due to seasonal temperature changes, the forces that drive the inflow and outflow, gravity and pressure gradient force, are strongest in the winter when Gulf temperature is lowest, and weakest in the summer when Gulf temperature is highest.

The use of simple pendulum motion to classify the kinematics of the two distinct circulations between the Gulf and the Indian Ocean, associated with the low and high salinity equilibria, shows that a perturbation that leads to transition from the low to high salinity equilibrium enhances the counterclockwise winter circulation and diminishes the clockwise summer circulation in the low salinity (Ic2) equilibrium (Fig. 4-2); and both of these are accomplished when such a perturbation decreases Gulf water surface elevation beyond the low salinity equilibrium winter water level and the additional salt that is transported into the Gulf leads to increase in Gulf density beyond its low salinity equilibrium summer value. Thus, the effect of a perturbation that leads to transition in Gulf equilibria from low to high salinity equilibrium is to decrease Gulf water surface elevation and increase Gulf salinity.
4.2 Sensitivity of Salinity Equilibria to Brine Discharge from Seawater Desalination Plants

A decadal numerical experiment was performed in GARM where a desalination perturbation (D1) was introduced into the Gulf at the low salinity equilibrium (Ic2) in order to test the sensitivity of this equilibrium to brine discharge from seawater desalination plants, and analyze the transition between and stability of the multiple Gulf equilibria. Brine from a desalination plant with salinity of 60g/kg is discharged continuously at a rate of 1.43m³/s into the Gulf at Ic2 equilibrium. And the plant is located in the shallow Arabian coast (Fig. 4-4) where most of the desalination plants in the Gulf are located.

The desalination perturbation (D1) causes a transition in the simulated Gulf salinity (Fig. 4-5) from Ic2 equilibrium value of salinity (≈36.9g/kg) to Ic1 equilibrium value of

Figure 4-3: Gulf water density for the low salinity equilibrium (Ic2), high salinity equilibrium (Ic1), all intermediate equilibria and the Indian Ocean.
Figure 4-4: Design of perturbation experiment to test the sensitivity of Gulf Equilibria to desalination; the point marked red is the desalination plant introduced into the Gulf at the low salinity equilibrium (Ic2). The brine has a salinity of 60 g/kg and is discharged at a rate of 1.4 m$^3$/s.

Salinity (~40.5-41 g/kg), passing through the salinities of the intermediate equilibria (Ic4, Ic5, Ic6). And this shows that Ic2, Ic4, Ic5 and Ic6 salinity equilibria are unstable to brine discharge from seawater desalination plants because the brine perturbation (D1) leads to a shift away from the salinities of these equilibria. However, the convergence of Gulf salinity to Ic1 equilibrium salinity shows that Ic1 equilibrium is stable, which further confirms the effect of the feedback property of the residual circulation associated with this equilibrium, which increases or decreases inflow into the Gulf from the ocean and outflow from the Gulf to the ocean in response to a positive or negative perturbation of Gulf density respectively.

Due to D1 perturbation, Gulf water surface elevation decreases continuously from its level in Ic2 equilibrium to Ic1 equilibrium water surface elevation, but this decrease is more rapid during the first four years (1981 - 1984) of the transition from Ic2 to Ic1 equilibrium than in the last six years (1985 - 1990) (Fig. 4-6). Since gravity, which depends on the difference in Gulf and Indian Ocean water elevations, drives the inflow from the Indian Ocean into the gulf, salt transport into the Gulf from the Indian ocean is more rapid in the first four years than in the last six years of the transition from Ic2 to Ic1 equilibrium. Furthermore,
the seasonal amplitude of salinity during the transition from Ic2 to Ic1 equilibrium increases continuously in the first four years of the transition (Fig. 4-5), which implies that the seasonal transport of salt out of the Gulf is low during this period. And since the outflow from the Gulf is driven by pressure gradient force, which depends on the difference between Gulf and Indian Ocean density, it follows that the increase in Gulf density is more rapid in the first four years than the last six years of the transition from Ic2 to Ic1 equilibrium.
Figure 4-6: Monthly Gulf water surface elevation when a desalination perturbation is applied to the Gulf at the low salinity (Ic2) equilibrium compared with the water surface elevation of the high salinity equilibrium (Ic1).
Chapter 5

Effect of Brine Discharge from Seawater Desalination Plants on the Salinity of the Gulf

5.1 Introduction

The six member countries of the Gulf Corporation Council (GCC), Bahrain, Kuwait, Qatar, United Arab Emirates, Oman and Saudi Arabia, have desalination plants with about 61% of the world’s seawater desalination capacity (Fig. 5-1), and the Gulf is the source of seawater and sink of brine for plants producing ≈80% of the GCC share of world’s desalination capacity (Lattemann and Hopner, 2008). Detailed environmental impact analysis is important for planning, construction and management of desalination plants, not only to avoid costly environmental problems with future plants, but also to guide the expansion of current plants (Hopner and Windleberg, 1996; Einav and Lokiec, 2003; Morton et al., 1996). However, a recent review study by Roberts et al. (2010) highlights the scarcity of quantitative peer reviewed environmental impact studies that are useful for design, placement and management of desalination plants.

The residual circulation between the Gulf and the Indian Ocean is a significant feature of the dynamics of the Gulf, and Hopner and Windleberg (1996) and Morton et al. (1996) have
observed that the effect of seawater desalination on the Gulf, at basin and regional scales, cannot be discussed separately without regard to the residual circulation. But previous impact studies of desalination plants in the Gulf have focused on interaction of brine discharge with tidal currents (Al-Barwani and Purnama, 2008), near-field (short-term) impact of brine discharge from single plants (Altayaran and Madany, 1992), and brine discharge along sections of the Gulf coast (Purnama et al., 2003). The objective in this chapter is to quantify, using basin and regional salinities, the interaction between brine discharge from the 24 largest desalination plants in the Gulf and the residual circulation in the Gulf.

Three numerical experiments, performed in the coupled Gulf-Atmosphere regional model (GARM), are analyzed and reported here. The dynamics of the residual circulation is simulated in the first experiment (Exp1), and brine discharges from the 24 largest desalination plants in the Gulf are introduced into the dynamics of the residual circulation in the second experiment (Exp2). The 24 plants are then separated into two groups, one of which is
Figure 5-2: Gulf surface salinity simulated in GARM; the most saline regions of the Gulf are also the shallowest regions on the Arabian Coast.

excluded in the third experiment (Exp3), in order to estimate the relative contribution of each group of plants to changes in basin and regional salinities due to brine discharge. Gulf basin and regional salinities, and the distribution of desalination plants are reviewed and described in the rest of this section. The experimental design, results and conclusions are given in sections two, three and four respectively.

5.1.1 Basin & Regional Salinities

The Gulf is one of the most saline oceanic basins in the world with a basin salinity estimate of 40.5 - 41g/kg, as shown in chapter three. It was also shown that salinity within the Gulf basin is higher in the shallow (Fig. 2-2) western and southwestern coast (Fig. 5-2). These shallow coastal environments within the Gulf have been grouped by Evans et al. (1973) into seven principal microenvironments: near-shore shelf, frontal reef, tidal deltas, frontal beaches and dunes, lagoonal channels, lagoonal terraces, and intertidal flats. Because these microenvironments are shallow and because no freshwater enters the Gulf at these regions, atmospheric climatic factors such as evaporation and air temperature have a stronger effect in
these regions, which lead to high water temperatures and salinities (Clarke and Keij, 1973). Discharge of brine from desalination plants into the Gulf is unlikely to increase the basin salinity of the Gulf due to the restoring effect of the residual circulation. However, because of the scarcity of detailed observed salinity data within the basin, especially in the shallow regions, the effect of the interaction of desalination activity and the residual circulation on regional salinities remains uncertain.

5.1.2 Distribution of Desalination Plants in the Gulf

Most of the seawater desalination plants in the Gulf (including all the largest plants) are located on the shallow Arabian Coast (Fig. 2-3). Thus, most of the brine discharged into the Gulf enters at the Arabian coast. Although the basin wide residual circulation is such that increase in Gulf water density, due to increase in salinity or decrease in temperature, leads to higher inflow into the Gulf from the Indian Ocean and hence increased mixing in the Gulf, weak interaction between coastal currents and the residual circulation may lead to salt accumulation and increase in regional salinities due to brine discharge from seawater desalination plants.

The residual circulation is the non periodic circulation that is left after subtraction of the periodic motion induced by tides (Sugden, 1963; Hunter, 1983; Nunes-Vas et al., 1990; Chao et al., 1992; Reynolds, 1993), and it is three dimensional and complex, but the general impression is that the circulation forms a cyclonic gyre within the Gulf. The inflowing surface current that enters along the Iranian coast is broadest and reaches the northern parts of the Gulf in the summer, but in the winter, the lateral extent is substantially reduced and the longitudinal extent is only about half of that during the summer. The dense saltier water that sinks to the bottom of the Gulf flows out from the southern region of the Strait of Hormuz. Since the spatiotemporal variation of the residual circulation in the Gulf determines the strength of its restoring effect at the regional scale, it is necessary to introduce seawater desalination plants into the dynamics of the residual circulation in order to quantify the effect of brine discharge on regional salinities in the Gulf. Additionally, salinity may be considered a tracer, hence, regional salt accumulation from brine discharge also highlights the regional accumulation of other chemical constituents of brine such as chlorinated hydrocarbons.
5.2 Experimental Design

The basis of all desalination processes is the removal of salt from seawater in order to produce potable water. For a given production capacity $V_p [m^3/d]$, the primary interaction of a seawater desalination plant with an oceanic basin involves the intake of a given volume of seawater $V_I [m^3/d]$ ($\approx 3$ times $V_P$) of salinity $S_I [g/kg]$, and discharge of brine (effluent $\approx 2 \times V_P$ and $\approx 1.5 \times S_I [g/kg]$) into the basin (Morton et al., 1996; Einav and Lokiec, 2003). Introducing $V_D [m^3/d]$ for the volume of brine discharge into the sea, and $\rho [kg/m^3]$ for density, the conservation of salt and water mass in the desalination process are given respectively by:

\begin{equation}
\rho_I V_I S_I = \rho_D V_D S_D \tag{5.1}
\end{equation}

\begin{equation}
\rho_D V_D = \rho_I V_I - \rho_P V_P. \tag{5.2}
\end{equation}

From Eq. 5.1 the mass of salt in brine discharge is the same as that in the intake water. But from Eq. 5.2, the mass of water in brine discharge is the difference of the mass of intake water and mass of potable water produced. Therefore, for a given oceanic basin, the long-term interaction of a seawater desalination plant with an oceanic basin, with regard to salt and water only, may be modeled as the inverse of freshwater discharge from a river into the oceanic basin. There are several methods of desalinating seawater including electrodialysis, electrodialysis reversal, reverse osmosis, multi-stage flash distillation, multi-effect distillation and vapor compression distillation, and these methods may have different ratio of intake to discharge capacity. But in this work, desalination plants are modeled as described above.

A dataset of 868 seawater desalination plants around and on the Gulf was compiled, including plants that are online, under construction and planned (Global Water Intelligence, 2016), and the production capacities of these plants span a wide range of values (Fig. 5-3). Because it would be impractical to simulate all 868 desalination plants in GARM, a criterion of desalination plants with capacity $\geq 100,000$ m$^3$/d was chosen as a cutoff for plants that will be introduced into the dynamics of the residual circulation simulated in GARM. All the 24 desalination plants (Fig. 5-4) that satisfy the cutoff criterion are located on the western coast of the Gulf (Fig. 5-5).
Three decadal (1981 -1990) experiments (Fig. 5-4) were performed in GARM under identical ocean and atmosphere initial and boundary conditions (as in the equilibrium experiments) in order to quantify the interaction between brine discharges from desalination plants and the residual circulation between the Gulf and the Indian Ocean. Decadal experiments were deemed sufficient due to the relatively short flushing time of the Gulf, and also, because the seasonal cycle dominates the variability of the Gulf system. Desalination plants are not included in the simulation of the dynamics of the residual circulation in the first experiment (Exp1). And the 24 desalination plants in the Gulf with capacity greater than 100,000 m$^3$/d (Fig. 5-4; Fig. 5-5) are introduced into the dynamics of the residual circulation in the second experiment (Exp2). For the third experiment (Exp3), the 24 largest desalination plants are separated into two groups with 10 plants located within 50 - 54E longitude in group one (Gp1) and 14 plants located outside 50 - 54E longitude in group two (Gp2). But only the plants in Gp2 are introduced into the dynamics of the residual circulation (Fig. 5-5) in experiment three (Exp3).
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**Experiment ID** | **Desalination** | **Plant ID**  
Exp1 | No | -  
Exp2 | Yes | 1 - 24  
Exp3 | Yes | 4-9,14,16,18-21,24  

Figure 5-4: Experiment design: the 24 desalination plants in the Gulf with capacity >100,000 m$^3$/d (status: O=online, and C=under construction). The plants simulated in each experiment are shown at the bottom of the table.

## 5.3 Results

### 5.3.1 Basin & Regional Salt Accumulation

The objective of the numerical experiments performed and reported in this chapter is to use changes in basin and regional salinities, when brine discharge from seawater desalination
Figure 5-5: Distribution of simulated desalination plants in Exp2, where brine discharges from the 24 plants in Tab. 1 are simulated, and Exp3, where brine discharge from plants located within 50 - 54E (Gp1) are excluded in the simulation.
plants are introduced into the dynamics of the residual circulation between the Gulf and the Indian Ocean, to quantify the effect of brine discharges on the Gulf. Since the dynamics of the residual circulation is simulated in Exp1 and brine discharge from the 24 largest desalination plants in the Gulf are added to the dynamics of the residual circulation in Exp2, comparison of salinities in Exp1 and Exp2, at basin and regional scales, then provides a way to quantify the effect of brine discharge into the Gulf. As expected, the basin salinity of the Gulf is mostly insensitive to brine discharge from the 24 largest plants because the basin salinity increased only by about $0.3$ g/kg (Fig. 5-6b). And this insensitivity is due to the restoring effect of the residual circulation which increases water inflow to the Gulf from the Indian Ocean when Gulf density increases due to increase in Gulf salinity or decrease in Gulf temperature.

Furthermore, the amplitude of the seasonal cycle of salinity, which is the difference between the annual maximum and minimum salinity, increased from about $0.5$ g/kg to $0.7$ g/kg when brine discharge from seawater desalination plants are introduced into the dynamics of the residual circulation (Fig. 5-6b). And since most of the salt in the Gulf comes from the Indian Ocean (Emery, 1956), this increase in the amplitude of the seasonal cycle suggests that the salt transport into and out of the Gulf is larger when brine discharge are introduced into the dynamics of the residual circulation in the Gulf; thus, introduction of brine discharges from seawater desalination plants into the dynamics of the residual circulation increases the velocity of inflow to the Gulf from the Indian Ocean and velocity of outflow from the Gulf to the Indian Ocean.

At the regional scale, however, some regions within the Gulf are more sensitive to brine discharge than other regions. Comparison of the time and depth averaged salinity in Exp1 and Exp2 shows an increase in salinity of the southwestern region of the Gulf, including the coasts of Bahrain, the southern coasts of Saudi Arabia, and the coast of United Arab Emirates (UAE), which indicates that these regions are the most sensitive to brine discharge from desalination plants (Fig. 5-6a). And the accumulation of salt in the southwestern region of the Gulf implies that the currents in this region, especially along the southern coasts of Saudi Arabia and UAE, are weakly connected to the residual circulation in the Gulf.

Two regions within the Gulf were selected for analysis of regional differences in sensitivity
to brine discharges from desalination plants. The first (Reg1) is the region of highest salt accumulation due to brine discharges from the 24 largest plants in the Gulf (Fig. 5-7a). Plant 1-3 in Bahrain and plant 15 in Saudi Arabia are located in Reg1, but the plants in Bahrain are located on the eastern coast of Bahrain (Fig. 5-5). Comparison of Exp1 and Exp2 shows a large increase in salinity of \( \approx 4.5 \text{g/kg} \) in Reg1 (Fig. 5-7b). And the high
Figure 5-7: (a) Region with the highest salt accumulation (Reg1; yellow shade), and corresponding mean salinity simulated in Exp 1-2 (b).

sensitivity to brine discharge in Reg1 suggests that the coastal currents in this region are the least connected to the residual circulation, which leads to salt accumulation within the region. The second region (Reg2) is the area up to 20km offshore from the Arabian coast of the Gulf (Fig. 5-8a), where the largest desalination plants in the Gulf are located (Fig. 5-5 top panel). The salinity of Reg2 increased from $\approx40.5$g/kg in Exp1 to $\approx42$g/kg in Exp2 due to brine discharges (Fig. 5-8b). However, there is no significant salt accumulation in the northwestern part of Reg2, including Kuwait and the northern coast of Saudi Arabia. And similarly, there is no significant salt accumulation in the southeastern part of Reg2 in eastern UAE. Hence, the increase in the salinity of Reg2 is mostly due to salt accumulation
5.3.2 Regional Sensitivity to Brine Discharge

Based on the spatial distribution of salt accumulation due to simulated brine discharges into the Gulf (Fig. 5-6a), the 24 desalination plants in Exp2 (Fig. 5-4) were separated into two groups in order to quantify the contribution of each group to salinity increase at basin and regional scales. The plants in Gp1, located within 50 - 54 E longitude, are excluded from Exp3, and the plants in Gp2, located outside 50 - 54E longitude, are included in Exp3.
Figure 5-9: (a) Time-averaged mean basin salinity difference (Exp3 - Exp1), and mean basin salinity simulated in Exp 1-3 (b).

The total production capacity of the 24 plants included in Exp2 is \( \approx 4.3 \text{km}^3/\text{yr} \), and the 10 plants in Gp1 and 14 plants in Gp2 produce respectively 35% and 65% of the total production capacity. Since the 24 largest desalination plants in the Gulf are included in the dynamics of the residual circulation in Exp2 and only the plants in Gp2 are included in the dynamics of the residual circulation in Exp3, comparison of salinity in Exp1 and Exp3 quantifies the
effect of brine discharges into the Gulf from plants in Gp2. And comparison of salinity in Exp2 and Exp3 quantifies the effect of brine discharges into the Gulf from plants in Gp1.

The basin salinity of the Gulf is less (more) sensitive to brine discharge from desalination plants in Gp2 (Gp1). Basin salinity increased from $\approx 40.5$ g/kg in Exp1 to $\approx 40.6$ g/kg in Exp3, while previously, basin salinity increased from $\approx 40.5$ g/kg in Exp1 to $\approx 40.8$ g/kg in Exp2 (Fig. 5-9b). This shows that brine discharges from plants in Gp1, which are included in Exp2 but excluded in Exp3, are responsible for about 65% of the increase in basin salinity, while brine discharge from plants in Gp2 contributes 35% of the increase in basin salinity. Regional salinities are also less (more) sensitive to plants in Gp2 (Gp1). And there is also a significant reduction in salt accumulation in the southwestern region of the Gulf (Fig. 5-9a).
especially along the southern coast of Saudi Arabia, when there are no brine discharge from plants located within 50 - 54E longitude (Gp1). Reg1 (Fig. 5-10b) salinity decreased from \( \approx 46.5 \text{g/kg} \) in Exp2 to \( \approx 42.5 \text{g/kg} \) in Exp3 (Fig. 5-10b), which shows that brine discharge from plants in Gp1 (Gp2) contribute \( \approx 65\% \) (\( \approx 35\% \)) of the increase in Reg1 salinity. And the contributions of brine discharge from plants in Gp1 and Gp2 to salinity increase in Reg2 (Fig. 5-11a) are similar to Reg1, 65\% and 35\% respectively, which further shows that increase in Reg2 salinity (Fig. 5-11) is due mainly to salt accumulation in the southwestern region of the Gulf. The larger inferred contribution of plants in Gp1 to increase in regional and basin salinities highlights the importance of placing desalination plants outside of 50 -
54E longitude in order to minimize the effect of brine discharge from desalination plants on the salinity of the Gulf.

### 5.3.3 Seasonal Variability of Salt Accumulation in the Gulf

The structure of the residual circulation within the Gulf varies spatially and temporally during the year due to spatiotemporal variability in Gulf water surface elevation, which controls the strength of the inflow of less saline water from the Indian Ocean into the Gulf, and spatiotemporal variability in the density of Gulf waters, which controls the strength of the outflow of dense hypersaline water from the Gulf into the Ocean. The seasonality of the change in salinity in the region with the highest salt accumulation [Reg1] (Fig. 5-12), due to the discharge of brine from the 24 largest desalination plants in Gulf, shows that the residual circulation is strongest (weakest) in this region in June (November) because there is a 1g/kg increase in the salinity of Reg1 from June to November. And similarly, the seasonality of the change in salinity in the region 20km offshore from the Arabian Coast [Reg2] (Fig. 5-13), due to the discharge of brine from the 24 largest desalination plants in Gulf, also shows that
Figure 5-13: Seasonality of salt accumulation in Reg2; the residual circulation is strongest (weakest) in this region in June (November).

the residual circulation is strongest (weakest) in this region in June (November) because there is a 0.6 g/kg increase in the salinity of Reg2 from June to November.

Thus, the seasonality of the change in salinity in Reg1 and Reg2 due to brine discharge into the Gulf suggests that the currents of the residual circulation within the Gulf, especially on the Arabian Coast, are strongest (weakest) in June (November), and this is confirmed by analysis of the seasonal vertical averaged velocity of the residual circulation within the Gulf. The residual circulation has a well defined structure in June (Fig. 5-14): strong inflow of up to 0.2 ms\(^{-1}\) from the Indian Ocean into the Gulf along the Persian Coast that extends up to 28\(^\circ\)N latitude and 50\(^\circ\)E longitude, and three cyclonic gyres are formed on the western boundary of this inflowing current; the corresponding outflow in the residual circulation in June, which has a velocity of up to 0.12 ms\(^{-1}\), starts along the Arabian Coast at 30\(^\circ\)N and begins to spread at 27\(^\circ\)N to cover most of the southern region of the Gulf before reaching the Strait of Hormuz.

However, analysis of the vertical averaged velocity of the residual circulation within the Gulf in November (Fig. 5-14) does not show a well defined structure: the velocities of the
Figure 5-14: Seasonal vertical averaged velocity in June (top) and November (bottom), which shows stronger coastal currents on the Arabian Coast in the structure of the residual circulation in June and weaker coastal currents on the Arabian Coast in the structure of the residual circulation in November.
residual circulation in most of the regions within the Gulf are small (< 0.04ms\(^{-1}\)); the magnitude, latitudinal and longitudinal extent of the inflow from the Indian Ocean into the Gulf along the Persian Coast is significantly reduced (up to 0.12ms\(^{-1}\) and 26°N latitude and 53°E longitude respectively); no gyres are formed within the Gulf but there is a small spread of the inflow to the southern part of the Gulf. There is no structure in the outflow from the Gulf to the Indian Ocean, and unlike the residual circulation in June, there are no strong currents along the Arabian Coast in the residual circulation in November. Because the spatial extent and magnitudes of the inflow and outflow velocities in the residual circulation are both smallest in November, salt accumulation will be larger in regions within the Gulf that are most sensitive to brine discharge from seawater desalination plants as shown by the seasonality of salinity change in Reg1 and Reg2.

Since the magnitudes and spatial extents of the inflow from the Indian Ocean to the Gulf and outflow from the Gulf to the Indian Ocean in the residual circulation are lowest and smallest respectively in November, the seasonal spatial distribution of change in salinity within the Gulf in November due to brine discharge is used to define critical zones within the Gulf of decreasing sensitivity to brine discharge from seawater desalination plants. Each contour line of the vertical averaged salinity difference in November (Fig. 5-15) separates the southwestern region of the Gulf, which is most sensitive to brine discharge from seawater desalination plants, into two regions: a southern region below the contour line where salinity change due to brine discharge is larger than the contour line value; and a northern region above the contour line where salinity change due to brine discharge is lower than the contour line value. Furthermore, each contour line ranks the pair of offshore distance and depth in the southwestern region of the Gulf in decreasing order of sensitivity to brine discharge from seawater desalination plants.

5.4 Conclusion

The study reported in this chapter uses change in salinity (at basin and regional scales) due to brine discharge to quantify the interaction between the residual circulation in the Gulf and brine discharge from the 24 largest desalination plants in the Gulf. Basin salinity
increased only by ≈0.3 g/kg and is mostly insensitive to brine discharge from the 24 largest desalination plants in the Gulf. However, there is significant sensitivity to brine discharge at the regional scale, especially in the southwestern region of the Gulf. Salinity in the region most sensitive to brine discharge, the area around Bahrain Island and southern coast of Saudi Arabia, increased by ≈4.5 g/kg. Brine discharge from desalination plants located within 50 - 54E longitude contribute 65% of the increase in salinity at both basin and regional scales, while brine discharge from plants outside of 50 - 54E longitude contribute 35% of the increase in regional and basin salinities. The spatial distribution of change in salinity in November, when the residual circulation within the Gulf is weakest, is used to define critical zones, where salt accumulation is minimized with increasing depth and distance offshore from the coast of the southwestern region of the Gulf with the largest salt accumulation due to brine discharge from seawater desalination plants.

Regional accumulation of salt in the Gulf, associated with the interaction of brine discharge from desalination plants and the residual circulation, leads to higher energy cost for
seawater desalination and reduction in the efficiency of plants that obtain seawater in the region where salinity increases. And increase in salinity may also increase the environmental stress on marine flora and fauna, especially in the most shallow southwestern region that includes a complex variety of microenvironments. In addition to high concentrations of salt, brine also contain high levels of other chemical compounds, foreign to the marine environment, such as additives, antifouling agents and corrosive substances. Since salinity may be considered a tracer, the components of other chemical compounds in brine may also accumulate to high concentrations in the southwestern region of the Gulf where salt is shown in this study to accumulate. Indeed, these foreign components, unlike salt, may be more toxic to marine life. The findings here underscore the importance of not placing future desalination plants in the southwestern region of the Gulf and provide a basis for design and management of desalination plants in the Gulf, so that costly environmental problems such as accumulation of salt and toxic substances can be avoided.
Chapter 6

Evaluation of the Placement of Brine Discharge Point in Seawater Desalination Plants in the Gulf

6.1 Introduction

The Gulf is the source of seawater and sink of brine for seawater desalination plants producing about half of the world's seawater desalination capacity (Lattemann and Hopner, 2008), and in chapter 5, the interaction between brine discharge from desalination plants in the Gulf and the residual circulation between the Gulf and the Indian Ocean was quantified using regional and basin salinities. The objective in this chapter is to evaluate the placement of brine discharge point in a seawater desalination plant in the Gulf that minimize regional salt accumulation and regional increase in salinity due to brine discharge.

Knowledge of the interaction of coastal currents and the basin scale residual circulation in the Gulf is necessary for placement of brine discharge point in seawater desalination plants that minimize regional salt accumulation. And two important factors for the siting of a seawater desalination plant are, first, the placement of the intake system for the delivery of seawater to the plant, and second, the placement of the plant discharge system for the removal of brine, the hypersaline outflow of the desalination process, which includes salt and
other chemicals such as cleaning and antifouling agents. If the brine discharge system is not placed properly and salt accumulates in the region where the plant intake system is located, then plant efficiency decreases and energy required for producing potable water increases due to intake of water with salinity higher than design salinity threshold. Moreover, regional accumulation of salt and other chemical constituents in brine may be harmful to marine life and lead to costly environmental problems in the complex coastal ecosystem.

Salinity maybe considered a tracer, and changes in regional salinity due to salt accumulation from brine discharge can be used to characterize the interaction of coastal currents and the residual circulation in the Gulf, a necessary first step in the siting of seawater desalination plants in the Gulf. Two decadal (10 years) numerical experiments are conducted using GARM and reported here in order to, first, characterize the interaction of coastal currents and the residual circulation in the Gulf, and second, illustrate the placement of a brine discharge system for a desalination plant that minimizes regional and basin salt accumulation.

6.2 Interaction of Coastal Currents with the Residual Circulation

Because salinity can be considered as a tracer in seawater, regional salinity within the Gulf can be used as a measure of the strength of the connection of coastal currents with the basin scale residual circulation. The larger (smaller) the difference between the salinity of a region within the Gulf and Gulf basin salinity, the weaker (stronger) is the connection of the coastal current in that region with the residual circulation. And regions that are weakly connected to the residual circulation are prone to salt accumulation due to brine discharge from seawater desalination plants.

A decadal numerical experiment which involves introducing brine discharges from the 24 largest desalination plants in the Gulf, located on the western and southwestern coasts, into the dynamics of the residual circulation (Exp1) was conducted in GARM and used to characterize the interaction between coastal currents and the residual circulation in the
<table>
<thead>
<tr>
<th>Plant ID</th>
<th>Country</th>
<th>Capacity (m$^3$)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bahrain</td>
<td>272,760</td>
<td>O</td>
</tr>
<tr>
<td>2</td>
<td>Bahrain</td>
<td>218,000</td>
<td>O</td>
</tr>
<tr>
<td>3</td>
<td>Bahrain</td>
<td>136,380</td>
<td>O</td>
</tr>
<tr>
<td>4</td>
<td>Kuwait</td>
<td>622,400</td>
<td>O+C</td>
</tr>
<tr>
<td>5</td>
<td>Kuwait</td>
<td>454,600</td>
<td>O</td>
</tr>
<tr>
<td>6</td>
<td>Kuwait</td>
<td>227,300</td>
<td>C</td>
</tr>
<tr>
<td>7</td>
<td>Kuwait</td>
<td>204,390</td>
<td>O</td>
</tr>
<tr>
<td>8</td>
<td>Kuwait</td>
<td>136,260</td>
<td>O</td>
</tr>
<tr>
<td>9</td>
<td>Kuwait</td>
<td>261,840</td>
<td>O</td>
</tr>
<tr>
<td>10</td>
<td>Qatar</td>
<td>741,160</td>
<td>O</td>
</tr>
<tr>
<td>11</td>
<td>Qatar</td>
<td>545,250</td>
<td>C</td>
</tr>
<tr>
<td>12</td>
<td>Qatar</td>
<td>654,606</td>
<td>O</td>
</tr>
<tr>
<td>13</td>
<td>Saudi Arabia</td>
<td>1,011,814</td>
<td>O+C</td>
</tr>
<tr>
<td>14</td>
<td>Saudi Arabia</td>
<td>1,025,000</td>
<td>O+C</td>
</tr>
<tr>
<td>15</td>
<td>Saudi Arabia</td>
<td>432,580</td>
<td>O</td>
</tr>
<tr>
<td>16</td>
<td>UAE</td>
<td>636,440</td>
<td>O</td>
</tr>
<tr>
<td>17</td>
<td>UAE</td>
<td>913,346</td>
<td>O</td>
</tr>
<tr>
<td>18</td>
<td>UAE</td>
<td>874,460</td>
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<td>19</td>
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<td>1,226,950</td>
<td>O</td>
</tr>
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<td>20</td>
<td>UAE</td>
<td>503,061</td>
<td>O</td>
</tr>
<tr>
<td>21</td>
<td>UAE</td>
<td>306,500</td>
<td>O</td>
</tr>
<tr>
<td>22</td>
<td>UAE</td>
<td>140,000</td>
<td>C</td>
</tr>
<tr>
<td>23</td>
<td>UAE</td>
<td>102,144</td>
<td>O</td>
</tr>
<tr>
<td>24</td>
<td>UAE</td>
<td>100,000</td>
<td>C</td>
</tr>
</tbody>
</table>

Figure 6-1: Experiment design: the 24 desalination plants in the Gulf with capacity $\geq 100,000$ m$^3$/d (status: O=online, and C=under construction). All 24 plants are simulated in Exp1 as shown in Fig. 6-2. In Exp2, the discharge location of Plant 15 is moved 77 km away from the coast where the depth is about 22 m.

The purpose of Exp1 is to characterize the interaction between coastal currents and the Gulf. The production capacity of seawater desalination plants in the Gulf that are online, under construction or planned span a wide range of values (Fig. 5-3). But for practical reasons, a criterion of desalination plants with capacity 100,000 m$^3$/day was used as a cutoff for plants introduced into the residual circulation and simulated in GARM in Exp1. And the 24 desalination plants that meet this criterion (Fig. 6-1) are all located on the western and southwestern coasts where the Gulf is most shallow (Fig. 6-2). Seawater desalination plants in the Gulf are introduced into the dynamics of the residual circulation in GARM according to the description in chapter 5.2.
residual circulation. The introduction of the 24 largest plants in the Gulf, online and under construction, increased the basin salinity from 40.5g/kg to \( \approx 40.8 \)g/kg (Fig. 6-3b). This minimal impact of desalination plants on Gulf basin salinity is not unexpected owing to the restoring effect of the residual circulation which brings less saline water from the Indian Ocean into the Gulf in response to Gulf density increase due to salinity increase. However, the spatial distribution of salinity, a measure of the regional accumulation of salt within the Gulf (Fig. 6-3a), shows that the southwestern and southern regions have the largest regional salinity within the Gulf relative to Gulf basin salinity. This suggests that the coastal currents in these regions are the least connected to the residual circulation, so that the restoring effect of the residual circulation is less effective in these regions.

Two regions within the Gulf were selected for analysis in order to further characterize the interaction of coastal currents with the residual circulation between the Gulf and the Indian Ocean. Region one (Reg1) is the area bounded by Bahrain, Qatar and the southern coast of
Figure 6-3: (a) Time-averaged and depth-averaged distribution of salinity of the Gulf with the 24 largest desalination plants introduced into the dynamics of the residual circulation; (b) monthly mean basin salinity of the Gulf.

Saudi Arabia, and it is the region in the Gulf with the largest salinity in Exp1 (Fig. 6-3a; Fig. 6-4a). Four plants, plant 1-3 (Bahrain) and 15 (Saudi Arabia), are located in Reg1 and the salinity of this region rose sharply from its initial value by $\approx 5$g/kg within the first year of the experiment, and reached a peak equilibrium salinity of $\approx 47$g/kg (Fig. 6-4b) at the end of the experiment. The high equilibrium salinity of Reg1 relative to Gulf basin salinity
Figure 6-4: (a) Region with the highest salt accumulation (Reg1; yellow shade), and the corresponding mean regional salinity simulated in Exp 1 (b)

indicates that the coastal currents in Reg1 are the least connected to the basin scale residual circulation. Thus, the restoring effect of the residual circulation is least effective in Reg1, which leads to the high salt accumulation in Reg1 due to brine discharge from seawater desalination plants.

Region two (Reg2) is the area 20km offshore from the Arabian coast of the Gulf where all the largest 24 seawater desalination plants are located (Fig. 6-5a). The salinity in Reg2 rose by \( \approx 2g/kg \) from its initial value up to an equilibrium value of \( \approx 42.4g/kg \), but the spatial distribution of salinity (Fig. 6-3a) shows that the increase in Reg2 salinity is due to salt accumulation in the western and southwestern regions of the Gulf, especially Reg1 with the
Figure 6-5: (a) Region up to 20km offshore from the Arabian Coast where the 24 largest desalination plants are located (Reg2; yellow shade), and corresponding mean regional salinity simulated in Exp 1 (b).

6.3 Placement of Brine Discharge Point in Seawater Desalination Plants

The primary objective in the placement of brine discharge point in seawater desalination plant in the Gulf is to minimize increase in regional salinities and salt accumulation due to brine discharge from seawater desalination plants. And the stronger the interaction between
Figure 6-6: Distribution of the 24 largest seawater desalination plants in the Gulf, with capacity $\geq 100,000$ m$^3$/d, that are introduced into the dynamics of the residual circulation and simulated in GARM Exp2; the brine discharge point of plant 15 (circled) located between Bahrain and the southern coast of Saudi Arabia in Exp1 is moved farther offshore ($\approx 77$ km) to deeper waters ($\approx 22$ m) in Exp-2.

Coastal currents in the place where brine is discharged and the basin scale residual circulation, the less likely it is that salt will accumulate in the place of brine discharge. Although the northwestern region of the Gulf is also shallow (Fig. 6-2), there is no salt accumulation in this region due to brine discharge from desalination plants (Fig. 6-3a), which suggests that the interaction of coastal currents with the basin scale residual circulation may not only be a function of depth of water, but also a function of distance to the coast. A second decadal experiment (Exp2) was conducted and compared to Exp1 in order to illustrate modification of the brine discharge point of an existing plant (plant 15), or placement of a new brine discharge point in a seawater desalination plant, which minimizes regional and basin salt accumulation. Exp2 (Fig. 6-6) involves moving the brine discharge location of plant 15, located between Bahrain and the southern coast of Saudi Arabia in Exp1, into deeper waters ($\approx 22$ m) and farther offshore from the coast ($\approx 77$ km from the coast).
Basin salinity decreased by $\approx 0.1$ g/kg (Fig. 6-7b) in Exp2 as a result of moving the brine discharge point of plant 15 into deeper waters and farther offshore from the Arabian coast. The spatial distribution of salinity difference between Exp1 and Exp2 shows that the largest salinity change, $\approx 2-3$ g/kg, is in Reg1 (Fig. 6-7a), which further highlights the importance of this region as the most prone to salt accumulation within the Gulf due to the weak interaction of the coastal currents there and the basin scale residual circulation.
The temporal evolution of salinity in Reg1 (Fig. 6-8b) also shows a sharp increase from its initial value, as in Exp1, by ≈4g/kg, but the equilibrium salinity in Exp2 (≈45g/kg) is ≈2g/kg less than the equilibrium value in Exp1 (47g/kg). Furthermore, the amplitude of the seasonal cycle of salinity in Reg1 is smaller in Exp2 than in Exp1, which suggests that the salinity of Reg1 in Exp1 may be the limit in which interaction between the coastal currents in Reg1 and the basin scale residual circulation become strong enough to suppress further salt accumulation in Reg1. Reg2 also show a decrease in salinity of ≈0.5g/kg in Exp2 (Fig. 6-9b). Salinity decreased in other areas within Reg2 which are not in Reg1 (Fig. 6-7), but similar to Exp1, the decrease in Reg2 salinity maybe attributed mostly to the decrease in Reg1 salinity.
Figure 6-9: (a) Region up to 20km offshore from the Arabian coast where the 24 largest desalination plants are located (yellow shade), and corresponding mean salinity simulated in Exp 1 and 2 (b).

6.4 Conclusion

Results from two decadal numerical experiments are used to characterize the interaction between coastal currents and the residual circulation between the Gulf and the Indian Ocean, and illustrate placement of brine discharge point in seawater desalination plants that minimizes regional and basin accumulation of salt due to brine discharge. The 24 largest desalination plants in the Gulf are introduced into the dynamics of the residual circulation in the first experiment, and regional salinities are used to characterize the strength of interaction between coastal currents on the Arabian Coast, where all the 24 desalination plants are located, and the residual circulation. There is no change from the initial salinity, and hence
no salt accumulation, in the northwestern region of the Gulf due to brine discharge from desalination plants, which implies that there is strong interaction between coastal currents there and the basin scale residual circulation. However, there is $\approx2-3\text{g/kg}$ change from initial salinity in the southwestern region due to brine discharge from desalination plants, which implies salt accumulation in this region and weak interaction between the coastal currents there and the basin scale residual circulation. Salinity increased by $\approx7\text{g/kg}$ in a sub-region within the southwestern region with the least interaction between the coastal current and the residual circulation.

The desalination plant closest to the region of highest salt accumulation in the first experiment was moved to deeper waters and farther offshore from the coast in the second experiment in order to illustrate placement of brine discharge point in a seawater desalination plant that minimizes increase in regional and basin salinities. Comparison of the first and second experiment showed that basin salinity decreased by $\approx0.1\text{g/kg}$. And salt accumulation decreased in the sub-region of the southwestern region with the least interaction between the coastal currents and the basin scale residual circulation, which led to $\approx2\text{g/kg}$ decrease in salinity from $\approx47\text{g/kg}$ in the first experiment to $\approx45\text{g/kg}$ in the second experiment.

Seawater intake systems for desalination plants are often located a few kilometers offshore, and increase in salinity at intake locations, due to accumulation of salt from brine discharged by desalination plants, is likely to increase the cost of energy for desalination and reduce the efficiency of producing potable water from seawater. Furthermore, since salt can be considered a tracer in seawater, regional salt accumulation is an indicator of regional accumulation of other chemical constituents of brine, such as cleaning and antifouling agent, used in the desalination process. These chemicals may indeed be more harmful to marine life and lead to costly environmental problems because, unlike salt, they are foreign to the marine environment. Placement of brine discharge point in deeper waters farther offshore, as illustrated here for a seawater desalination plant in the southwestern region of the Gulf, involves the short-term additional cost of assessing several locations and constructing a brine delivery system to a location with strong interaction between local currents and the residual circulation between the Gulf and the Indian Ocean in order to minimize salt accumulation. But the long-term benefit of this short-term cost includes avoiding future increase in the
cost of producing potable water from seawater and costly environmental problems to marine life due to the accumulation of salt and other chemical constituents of brine. Moreover, the illustration of the placement of brine discharge point in seawater desalination plants given here can also be used to modify existing desalination plants in the Gulf in order to improve efficiency of potable water production and reduce existing regional salt accumulation.
Chapter 7

Analysis of Trends in Equilibrium Properties of the Gulf

7.1 Introduction

The Gulf is a vital water resource for the eight countries with coasts on the Gulf, and climatic variability and change in the atmosphere and Indian Ocean may affect the Gulf in various ways. Hence, analysis of trends in long-term observations of Gulf water properties, water elevation, temperature and salinity are necessary to understand and quantify the effects of climatic change and variability on the Gulf. The objective in this chapter is to quantify the trends in Gulf water elevation, temperature and salinity during the period 1993 to 2014.

Ocean surface elevation (altimetry) is an essential variable for oceanographic research because the elevation of the ocean is a state variable that integrates variation in density (due to variation in temperature, salinity and pressure) and mass resulting from the interaction of the ocean with the atmosphere and continents (Garcia et al., 2007; Cheng and Qi, 2010; Wei and Min, 2015). Continuous time series of satellite derived ocean altimetry that is suitable for climate monitoring and research at the global and regional scales has only been available for the past $\approx 23$ years. However, no report of the application of this dataset to investigation of trends in Gulf elevation could be found in peer reviewed journals, which may be because external independent sources of altimetry measurements that validate satellite derived altimetry are limited for the Gulf (Ablain et al., 2015).
Scarcity of observed salinity data, especially for the west-southwest regions where most of the desalination plants in the Gulf are located, also limits the investigation of Gulf salinity trends. And heavy marine traffic and low water elevation in the shallow regions also makes data collection difficult and expensive (Reynolds, 1993). In order to overcome the limitation posed by the sparsely observed Gulf salinity in this study, regression models are developed for salinity as a function of water elevation and temperature using Gulf salinity, water elevation and temperature simulated in the dynamics of the residual circulation in GARM. And the regression models are then used with observed time series of Gulf water elevation and temperature, for the period 1993 to 2014, to compute the trends of Gulf salinity for the same period.

### 7.2 Seasonal Characteristics

Meteorological factors strongly affect the Gulf because it is shallow, mostly surrounded by land (Fig. 2-1), and the climate in the Gulf region is arid. Also, because the Gulf is shallow, the effect of pressure (due to the weight of overlying water) on the density of Gulf waters is secondary to that of temperature and salinity. The seasonal cycle dominates variability of the Gulf system (Xue and Eltahir, 2015). The minimum and maximum Gulf basin temperatures (Fig. 7-1b) occur in February and August during the winter and summer seasons respectively (Tab. 7.1). But the minimum and maximum Gulf basin salinity (Fig. 7-1c) occur in August and January during the summer and winter seasons respectively (Tab. 7.1); this inversion between the seasonal maxima and minima of Gulf temperature and salinity highlights the fact that the mass of salt transported into the Gulf from the Indian Ocean is higher during the winter than in the summer (Fig. 4-2). The minimum and maximum Gulf water surface elevations (Fig. 7-1a) occurs in May and August during the spring and summer seasons respectively (Tab. 7.1).
Table 7.1: Gulf seasons and months in each season

<table>
<thead>
<tr>
<th>Season</th>
<th>Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>December, January, February</td>
</tr>
<tr>
<td>Spring</td>
<td>March, April, May</td>
</tr>
<tr>
<td>Summer</td>
<td>June, July, August</td>
</tr>
<tr>
<td>Fall</td>
<td>September, October, November</td>
</tr>
</tbody>
</table>

Figure 7-1: Observed Gulf water elevation (a) obtained from satellite altimetry measurements; Gulf seasonal temperature (b) obtained from NOAA analysis OISST-AVHRR; Gulf seasonal salinity (c) simulated in a coupled Gulf-Atmosphere Regional Model (GARM).
7.3 Data & Data Analysis

The altimetry and sea surface temperature data used in the analysis of trends have been described in chapter 3.2, and the principal method used for the analysis of trends in Gulf temperature and water level is simple linear regression: the time series of temperature and water level are filtered (by subtracting the average annual mean) in order to obtain departures from the average annual mean, and linear regression is then applied to these departures in order to compute trends. To overcome the scarcity of detailed observed salinity for the Gulf, three steps are used to compute Gulf salinity trends: first, a linear regression model (RM) of salinity as a function of temperature and water level is obtained from GARM, which simulates the residual circulation in the Gulf; second, the RM and observed Gulf temperature and water level are used to compute Gulf salinity; third, Gulf salinity computed with the RM is filtered (by subtracting the average annual mean) in order to obtain departures from the average annual mean and a linear regression is then applied to these departures of salinity in order to compute Gulf salinity trends.

Four different least square RMs (RM1, RM2, RM3, RM4) are derived from three different decadal (1981 - 1990) experiments (Exp1, Exp2, Exp3) in the GARM (Fig. 7-2), and these RMs are then used to reconstruct the Gulf salinity simulated in Exp1 in order to check the reliability of the approach used here to compute Gulf salinity trends. RM1 is derived at the monthly time scale using monthly departures from climatological means of Gulf temperature (T), salinity (S) and water elevation (WE) simulated in Exp1 (Eq. 7.1); then RM1 is used with monthly departures of Gulf temperature and water elevation in Exp1 in order to obtain monthly departures of Gulf salinity, which are then added to the climatological means (CM) of salinity in Exp1 in order to reconstruct Gulf salinity simulated in Exp1. RM2 is derived at the annual time scale using the annual means of temperature, salinity and water elevation simulated in Exp2 (Eq. 7.2); RM2 is then used with the annual means of temperature and water elevation simulated in Exp1 in order to reconstruct Gulf salinity simulated in Exp1. RM3 is derived at the annual time scale from Exp3 (Eq. 7.3) and applied in the same manner as RM2, to reconstruct Gulf salinity simulated in Exp1. Lastly, RM4 is derived at the annual time scale by combining annual means from Exp1, Exp2 and Exp3 (Eq. 7.4) and applied in
Figure 7-2: Water elevation (top panel), SST (middle panel) and salinity (bottom panel) from three simulations in the Gulf-Atmosphere Regional Model (GARM): the water elevation, temperature and salinity values plotted here are used to derive four regression models (RM1, RM2, RM3, RM4), which are then used to compute the trend of Gulf salinity.
Figure 7-3: Gulf salinity obtained with the four regression models (RM1, RM2, RM3, RM4) compared to Gulf salinity simulated in the Gulf-Atmosphere Regional Model (GARM).

Gulf salinity reconstructed with RM1, RM3, and RM4 fits better than RM2 to Gulf salinity simulated in Exp1 (Fig. 7-3). However, RM1 does not reproduce the annual variability of Gulf salinity in Exp1, which is reproduced by RM2, RM3, and RM4. The $R^2$ value (Tab. 7.2) of RM1 (10%) is also significantly smaller than the $R^2$ values of RM2 (99%), RM3 (95%), and RM4 (99%), which shows that RM1 explains a smaller percentage of the variance in the reconstructed monthly departures of Gulf salinity. Since RM1 was derived using monthly departures from climatological means of Gulf temperature, salinity and water elevation simulated in Exp1, the small $R^2$ of RM1 further highlights the dominance of the
seasonal cycle in the variability of the Gulf system.

Table 7.2: R squared values of the regression models used to compute the trend of Gulf salinity.

<table>
<thead>
<tr>
<th>Regression Model</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>RM1</td>
<td>0.1</td>
</tr>
<tr>
<td>RM2</td>
<td>0.99</td>
</tr>
<tr>
<td>RM3</td>
<td>0.95</td>
</tr>
<tr>
<td>RM4</td>
<td>0.99</td>
</tr>
</tbody>
</table>

7.4 Trend of Water Elevation, Temperature & Salinity.

Table 7.3: Gulf water elevation trend for 22 years (1993 - 2014).

<table>
<thead>
<tr>
<th>1993 - 2014</th>
<th>Gulf water surface elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual trend (mm/yr)</td>
<td>3.3</td>
</tr>
<tr>
<td>Total trend (mm/22 yrs)</td>
<td>72.6</td>
</tr>
<tr>
<td>95% acceptance zone (2 sided)</td>
<td>(-8, 8)</td>
</tr>
<tr>
<td>90% acceptance zone (2 sided)</td>
<td>(-6.7, 6.7)</td>
</tr>
</tbody>
</table>

Gulf water elevation increased (Fig. 7-4) annually by 3.3 mm up to a total of ~73 mm from 1993 to 2014 (Tab. 7.3). And local trends, shown by the 2 yr moving average curve of the water elevation time series (Fig. 7-4), indicate significant inter-annual variability in Gulf water elevation. The computed annual Gulf water elevation trend is small and falls within a 90% and 95% acceptance zone, which suggests that this annual water level trend may be due to natural variability. Moreover, in the residual circulation between the Gulf and the Indian Ocean, the inflow from the Indian Ocean into the Gulf is driven by gravity, which is a function of the difference between the water level of the Gulf and the water level of the Indian Ocean. Therefore, if the water elevation of the adjacent Indian Ocean does not change during the period 1993 - 2014, then the ~73mm increase in Gulf water elevation during 1993
Figure 7-4: Annual departures of water elevation of the Gulf for the period 1993 to 2014. The trend line is obtained with simple linear regression, and the moving average window is 2 years.

- 2014 suggests a weakening of the inflow into the Gulf due to the residual circulation during the same time period.

Gulf temperature also increased (Fig. 7-5) annually by about 0.09°C up to a total of 1.9°C from 1993 to 2014 (Tab. 7.4). But this annual trend also falls within the 90% and 95% acceptance zones, which suggests that this trends may not be significant or maybe due to climate change. However, the 2 yr moving average curve of Gulf temperature shows significant inter-annual variability (Fig. 7-5) and because the dynamics of the Gulf is strongly

Table 7.4: Gulf sea surface temperature (SST) trend for 22 years (1993 - 2014).

<table>
<thead>
<tr>
<th>1993 - 2014</th>
<th>Gulf sea surface temperature (SST)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual trend (°C/yr)</td>
<td>0.09</td>
</tr>
<tr>
<td>Total trend (°C/22yrs)</td>
<td>1.9</td>
</tr>
<tr>
<td>95% acceptance zone (2 sided)</td>
<td>(-0.32, 0.32)</td>
</tr>
<tr>
<td>90% acceptance zone (2 sided)</td>
<td>(-0.27, 0.27)</td>
</tr>
</tbody>
</table>
coupled to the Indian Ocean, small Gulf temperature trends, such as shown here, may have significant impact within the Gulf. Evaporation only removes freshwater, and the salt associated with the inflow of less saline water from the Indian Ocean into the Gulf is removed through the residual circulation as bottom outflow of dense hypersaline water from the Gulf to the Indian Ocean. And pressure gradient force, which is a function of the difference of Gulf water density and Indian Ocean water density, drives the outflow of the residual circulation. Since the density of water decreases as temperature of the water increases, if the density of the adjacent Indian Ocean does not change during the period 1993 - 2014, then the 1.9°C increase in Gulf temperature during the period 1993 - 2014 suggests a weakening of the outflow from the Gulf due to the residual circulation.

Detailed observed salinity for the Gulf, especially in the shallow west and southwestern regions where the largest desalination plants are located, is scarce. Hence, regression models (RM) of salinity as a function of Gulf water elevation and temperature, derived from the simulated values of salinity, temperature and water elevation in the GARM are used to
Figure 7-6: Annual departures of salinity of the Gulf for the period 1993 to 2014 obtained with regression model one (RM1). The trend line is obtained with simple linear regression and the moving average window is 2 years.

Table 7.5: Gulf salinity trend for 22 years (1993 - 2014) obtained with RM1.

<table>
<thead>
<tr>
<th>Year</th>
<th>Gulf Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 - 2014</td>
<td>-0.0091</td>
</tr>
</tbody>
</table>

- Annual trend (g/kg/yr): -0.0091
- Total trend (g/kg/22yrs): -0.20
- 95% acceptance zone (2 sided): (-0.021, 0.021)
- 90% acceptance zone (2 sided): (-0.018, 0.018)

Table 7.6: Gulf salinity trend for 22 years (1993 - 2014) obtained with RM2.

<table>
<thead>
<tr>
<th>Year</th>
<th>Gulf Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 - 2014</td>
<td>-0.0071</td>
</tr>
</tbody>
</table>

- Annual trend (g/kg/yr): -0.0071
- Total trend (g/kg/22yrs): -0.16
- 95% acceptance zone (2 sided): (-0.024, 0.024)
- 90% acceptance zone (2 sided): (-0.02, 0.02)
Figure 7-7: Annual departures of salinity of the Gulf for the period 1993 to 2014 obtained with regression model two (RM2). The trend line is obtained with simple linear regression and the moving average window is 2 years.

compute the trend of Gulf salinity. Four regression models (RM1, RM2, RM3, RM4) are derived from three experiments (Exp1, Exp2, Exp3) in the GARM, and the four RMs are used to compute Gulf salinity trends in order to check the reliability of this approach for estimating the trend of salinity. All four RMs show a decreasing trend of Gulf salinity (Fig. 7-6 - 7-9), and this consistency increases confidence in the reliability of the approach used here to estimate the trend of Gulf salinity. RM1 shows the largest annual decrease in Gulf salinity of -0.009g/kg up to a total of -0.20g/kg from 1993 to 2014 (Tab. 7.5). RM2, RM3, and RM4 show annual decreasing trends in Gulf salinity of -0.0071g/kg, -0.0070 and -0.0071 up to totals of -0.16g/kg, -0.15g/kg and -0.16g/kg respectively from 1993 to 2014 (Tab. 7.6 - 7.8). However, the annual trends of Gulf salinity computed with the four regression models fall within the 90% and 95% acceptance zones, which suggests that the computed trends for Gulf salinity may not be statistically significant.

The residual circulation reflects the strong coupling between the dynamics of the Gulf and the Indian Ocean. There are several sources of salt into the Gulf, but the primary source
Figure 7-8: Annual departures from average annual mean salinity of the Gulf for the period 1993 to 2014 obtained with regression model three (RM3). The trend line is obtained with simple linear regression and the moving average window is 2 years.

Table 7.7: Gulf salinity trend for 22 years (1993 - 2014) obtained with RM3.

<table>
<thead>
<tr>
<th></th>
<th>Gulf Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 - 2014</td>
<td></td>
</tr>
<tr>
<td>Annual trend (g/kg/yr)</td>
<td>-0.0070</td>
</tr>
<tr>
<td>Total trend (g/kg/22yrs)</td>
<td>-0.15</td>
</tr>
<tr>
<td>95% acceptance zone (2 sided)</td>
<td>(-0.020, 0.020)</td>
</tr>
<tr>
<td>90% acceptance zone (2 sided)</td>
<td>(-0.016, 0.016)</td>
</tr>
</tbody>
</table>

Table 7.8: Gulf salinity trend for 22 years (1993 - 2014) obtained with RM4.

<table>
<thead>
<tr>
<th></th>
<th>Gulf Salinity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 - 2014</td>
<td></td>
</tr>
<tr>
<td>Annual trend (g/kg/yr)</td>
<td>-0.0071</td>
</tr>
<tr>
<td>Total trend (g/kg/22yrs)</td>
<td>-0.16</td>
</tr>
<tr>
<td>95% acceptance zone (2 sided)</td>
<td>(-0.027, 0.027)</td>
</tr>
<tr>
<td>90% acceptance zone (2 sided)</td>
<td>(-0.022, 0.022)</td>
</tr>
</tbody>
</table>
Figure 7-9: Annual departures from average annual mean salinity of the Gulf for the period 1993 to 2014 obtained with regression model four (RM4). The trend line is obtained with simple linear regression and the moving average window is 2 years.

is the adjacent Indian Ocean (Emery, 1956). Thus, the decreasing trend of Gulf salinity is likely due to increase in the mixing of Gulf waters by the residual circulation, which is a function of both the inflow to the Gulf from the Indian Ocean and outflow from the Gulf to the Indian Ocean. In order to further assess the strength of the residual circulation inflow into the Gulf from the Indian Ocean and determine whether the decreasing trend in Gulf salinity is due to increased mixing of Gulf waters by Indian Ocean water, the trends in water elevation of the Indian Ocean (an area comparable in size to the Gulf) for the period 1993-2014 are computed and compared to trends of water elevation in the Gulf.

The water elevation of the IO increased annually by 20.5 mm up to a total of 450 mm during the period 1993-2014 (Fig. 7-10, Tab. 7.9), and this trend is higher than the trend of Gulf water elevation (3.3 mm/yr, up to a total of 73 mm/22yr). Moreover, the annual trend of Indian Ocean water elevation falls outside the 90% and 95% acceptance zone, which implies that this annual trend is significant, and hence, the hypothesis that this annual trend is due to natural variability can be rejected. Therefore, relative to the Indian
Figure 7-10: Annual departures from average annual mean water surface elevation of the Indian Ocean for the period 1993 to 2014. The trend line is obtained with simple linear regression and the moving average window is 2 years.

Table 7.9: Trend of Indian Ocean water elevation for 22 years (1993 - 2014); an area of the Indian Ocean, comparable in size to the Gulf, is used to compute water elevation trends in the Indian Ocean.

<table>
<thead>
<tr>
<th></th>
<th>Indian Ocean water surface elevation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1993 - 2014</td>
<td></td>
</tr>
<tr>
<td>Annual trend (mm/yr)</td>
<td>20.5</td>
</tr>
<tr>
<td>Total trend (mm/22 yrs)</td>
<td>450</td>
</tr>
<tr>
<td>95% acceptance zone (2 sided)</td>
<td>(-16, 16)</td>
</tr>
<tr>
<td>90% acceptance zone (2 sided)</td>
<td>(-12.7, 12.7)</td>
</tr>
</tbody>
</table>

Ocean water elevation, Gulf water elevation decreased annually by 17.1 mm up to a total of 377 mm during the period 1993 - 2014. And because the inflow into the Gulf due to the residual circulation is driven by gravity flow (which is a function of the difference in the water elevations of the Gulf and IO), the decrease in Gulf water elevation relative to the Indian Ocean suggests a stronger residual circulation inflow into the Gulf from the Indian Ocean, and increased mixing of Gulf waters. Thus, the small decreasing trend in Gulf salinity, which
enhances expansion of Gulf waters due to increasing temperature, may be attributed to the increasing trend in Indian Ocean water elevation.

### 7.5 Conclusion

The objective of this chapter is to analyze the trends in Gulf water surface elevation, sea surface temperature and salinity. Satellite derived altimetry data and analyzed SST data are used to compute the trends of water elevation and temperature in the Gulf during the period 1993 - 2014. And, due to the scarcity of observed salinity data, four regression models of salinity as a function of water elevation and temperature, derived from experiments in the GARM that simulates the residual circulation in the Gulf are used with satellite derived altimetry and analyzed SST of the Gulf to compute the trend of salinity. Gulf water elevation increased by 3.3 mm/yr (72.6 mm/22yrs) while Gulf sea surface temperature increased by 0.09°C/yr (1.9°C/22yrs) The four regression models used to compute the trend of Gulf salinity show a decreasing trend in Gulf salinity: RM1 (-0.009 g/kg/yr and -0.20 g/kg/22yrs); RM2 (-0.0071 g/kg/yr and -0.16 g/kg/22yrs); RM3 (-0.007 g/kg/yr and -0.15 g/kg/22yrs); RM4 (-0.0071 g/kg/yr and -0.16 g/kg/22yrs).

The computed trends in Gulf water surface elevation, SST and salinity are all within the 95% and 90% acceptance zone in each variable, hence, the magnitudes of these trends are not statistically significant, probably reflecting real trends but of small magnitudes. However, the Gulf is tightly coupled to the Indian Ocean through the dynamics of residual circulation and the calculated trends in Gulf water surface elevation and salinity may also be due to increasing trends in the water surface elevation of the Indian Ocean. The annual trends in the Indian Ocean water surface elevation (20.5mm) are significant and likely not due to natural variability. Therefore, the decreasing trends in Gulf salinity may be due to increased mixing of Gulf waters with less saline Indian Ocean water; a consequence of higher lateral transport into the Gulf from the Indian Ocean due to increased water elevation of the Indian Ocean relative to the Gulf. And the decreasing trend of Gulf salinity may enhances increase in Gulf water surface elevation.

The dynamics of the Gulf is tightly coupled with the Indian Ocean; therefore, estimates
of trends in the water properties of the Indian Ocean may be useful for interpreting trends in Gulf water surface elevation, SST and salinity. Furthermore, since brine discharge from seawater desalination plants in the Gulf also contains high levels of metal ions and other chemical compounds foreign to the marine environment such as additives, antifouling agents and corrosive substances, estimates of trends in bioaccumulation of these metal ions and chemicals in marine flora and fauna can be used to infer regional strengthening or weakening of the restoring effect of the residual circulation by which the Gulf is flushed with water from the Indian Ocean. Lastly, the findings here highlight the need for investigating the interaction of brine discharge from desalination plants with the dynamics of the Gulf under a changing climate.
Chapter 8

Conclusion

8.1 Summary of Work

The arid climate in the Persian Gulf region leads to extremely high evaporation rates from the
Gulf (≈1.84 m/yr) that far exceeds freshwater inflow into the Gulf, mainly from precipitation
and some from river inflow. A residual circulation between the Gulf and the Indian Ocean
exists such that saline water flows into the Gulf from the Indian Ocean in order to balance
the freshwater deficit due to high evaporation rates, and since evaporation only removes
freshwater, the salt associated with this inflow from the Indian Ocean is removed in dense
saline water that sinks to lower layers and exits the Gulf into the Indian Ocean.

The Gulf is an important water body in the hydrology of Southwest Asia because the
water resource of the Gulf is vital to the well-being of the population and economies of many
Gulf countries that lack sufficient renewable freshwater resources and obtain their potable
water by desalinating seawater from the Gulf. The Gulf is also the sink of hypersaline brine
from seawater desalination plants, and since brine has very high salinity and consists of metal
ions, chlorinated hydrocarbons and other chemicals, which may be toxic to marine life, the
sustainability of seawater desalination in the Gulf is a pressing hydrologic problem. The
guiding vision for the work in this thesis is to provide a basin scale environmental analysis of
the impact of desalination on the Gulf in order to establish a strong foundation that promotes
the sustainability of seawater desalination in the Gulf. The four main contributions of this
thesis are summarized below.
The first contribution of this thesis reported in chapters 3 and 4 is the identification of the equilibrium state variables of the Gulf including a new estimate of Gulf basin salinity of \(\approx 40.5 \text{ - } 41\, \text{g/kg}\). Six numerical experiments performed in a coupled Gulf-Atmosphere Regional Model (GARM) that simulates the dynamics of the residual circulation between the Gulf and the Indian Ocean are analyzed in order to establish the equilibrium state variables of the Gulf. It is found that the Gulf has multiple salinity equilibria under the same atmospheric forcing and ocean boundary conditions. For the same Gulf basin temperature, two distinct salinity equilibria were found: a low salinity (Ic2) equilibrium (\(\approx 36.8\, \text{g/kg}\)) and a high salinity (Ic1) equilibrium (\(\approx 40.5 \text{ - } 41\, \text{g/kg}\)); and three other representative intermediate salinity equilibria were found with salinities between the those of Ic2 and Ic1 equilibria.

The surface temperature during winter and summer in both the high and low salinity equilibria are similar, but the seasonal variability of basin temperature plays an important role in differentiating the circulations between the Gulf and the Indian Ocean that are associated with Ic1 and Ic2 equilibria. Gulf seasonal minimum and maximum water density in the two equilibria varies over a range of \(\approx 3\, \text{kg/m}^3\) because of the large difference between the seasonal minimum and maximum basin temperature (\(\approx 13^\circ\text{C}\)). When Gulf water is heavier than Indian Ocean water, due to the higher density of Gulf water such as in Ic1 equilibrium, the vertical overturning circulation between the Gulf and the Indian Ocean is counterclockwise\(^1\) because Gulf waters sinks and exits the Gulf in bottom layers while Indian Ocean water floats and enters the Gulf in top layers. But when Gulf water is lighter than Indian Ocean waters, due to the lower density of Gulf water such as in Ic2 equilibrium, the vertical overturning circulation between the Gulf and the Indian Ocean is clockwise because Gulf water floats and exits the Gulf in top layers while Indian Ocean water enters the Gulf in bottom layers.

Furthermore, it is shown that Ic2 equilibrium is unstable because a desalination perturbation leads to a transition of the Gulf state from Ic2 to Ic1 salinity equilibrium, which is a stable equilibrium. The stability of Ic1 equilibrium is due to the restoring effect of the residual circulation between the Gulf and the Indian Ocean whereby a perturbation that increases Gulf density (due to increase in salinity or decrease in temperature) leads to an

\(^1\)for an observer facing north
increase in the inflow into the Gulf from the Indian Ocean and outflow from the Gulf to the Indian Ocean; and the inverse is true for a perturbation that leads to a decrease in Gulf density (due to decrease in salinity or decrease in temperature).

The rapid growth of commercial desalination in the Gulf has renewed the urgency for an estimate of the basin salinity, which has been difficult to obtain due to scarcity of observation data, and the most comprehensive surface salinity data from a 1992 expedition is limited in spatiotemporal coverage. Instead, satellite altimetry data is used to constrain the simulated water surface elevation in GARM in order to provide an estimate of Gulf basin salinity. Satellite altimetry data measures the water surface elevation in the Gulf, which is a function of the prevailing basin temperature and basin salinity, and GARM simulates the water surface elevation in the Gulf for the different equilibria. Since the simulated basin temperature distribution is similar in Ic2 and Ic1, comparison of the observed and simulated water surface elevation is used to infer the prevailing basin salinity. Thus, a new estimate of Gulf basin salinity in the range 40.5 - 41 g/kg, which corresponds to the salinity of Ic1 equilibrium, is provided for the Gulf.

In the second contribution of this thesis reported in chapter 5, seawater desalination plants are introduced into the simulated dynamics of the residual circulation in the Gulf and changes in basin and regional salinities are used to quantify the impact of brine discharge from seawater desalination plants on the Gulf. Three numerical experiments were performed in the GARM in order to quantify the effect of brine discharge on the Gulf: only the residual circulation between the Gulf and the Indian Ocean is simulated in the first experiment; brine discharges from the 24 largest desalination plants in the Gulf is introduced into the dynamics of the residual circulation in the second experiment; and in the third experiment, seawater desalination plants located within 50° - 54°E longitude are not included in the dynamics of the residual circulation.

Comparison of the results of the three numerical experiments shows that basin salinity increased only by ≈0.3 g/kg and is mostly insensitive to brine discharge from seawater desalination plants. However, there is significant sensitivity to brine discharge at the regional scale, especially in the southwestern region of the Gulf. Salinity in the region most sensitive to brine discharges, area around Bahrain Island and southern coast of Saudi Arabia, increased
by \( \approx 4.5 \text{ g/kg} \). Brine discharge from desalination plants located within 50 - 54E longitude contributed 65% of the increase in salinity at both basin and regional scales, while brine discharge from plants outside of 50 - 54E longitude contributed 35% of the increase in regional and basin salinities. The high contribution of brine discharge from plants located between 50 - 54E to regional salinity increase highlights the importance of not placing future desalination plants in this region. Furthermore, since salinity may be considered a tracer in seawater, the high contribution of brine discharge from plants within 50 - 54E to increase in regional salinities suggests that the plants in these regions are the primary source of other constituents of brine such as metal ions, chlorinated hydrocarbons and cleaning and antifouling chemicals used in the desalination process.

The third contribution of this thesis reported in chapter 6 is a proposal for placing brine discharge delivery systems that minimize salt accumulation due to brine discharges from seawater desalination plants. Because the Gulf is shallow, and due to the spatiotemporal variability of the residual circulation between the Gulf and the Indian Ocean, there is spatiotemporal variability in the interaction between coastal currents and the residual circulation. Thus, the restoring effect of the basin scale residual circulation is less effective in regions within the Gulf where coastal currents are not well connected to the residual circulation. Two numerical experiments were performed in the GARM in order to illustrate the placement of brine discharge systems that minimize salt accumulation due to brine discharges. In the first experiment, the 24 largest desalination plants in the Gulf are introduced into the dynamics of the residual circulation and regional salinities are used to characterize the strength of interaction between coastal currents on the Arabian Coast, where all the 24 desalination plants are located, and the basin scale residual circulation between the Gulf and the Indian Ocean. In the second experiment, the brine discharge of a plant closest to the region with the largest salt accumulation in the first experiment was moved farther offshore (from 2km to 77 km) into deeper waters (from 12 m to 22 m).

Comparison of the first and second experiment showed that basin salinity decreased by \( \approx 0.1 \text{ g/kg} \) when the brine discharge point was moved offshore into deeper waters, and salt accumulation decreased in the sub-region of the southwestern region with the least interaction between the coastal currents and the basin scale residual circulation, which led
to \( \approx 2 \text{g/kg} \) decrease in salinity from \( \approx 47 \text{g/kg} \) in the first experiment to \( \approx 45 \text{g/kg} \) in the second experiment. Decrease in salinity in the region of largest salt accumulation in experiment one, due to placing the brine discharge point of the plant adjacent to this region farther offshore into deeper waters in experiment two, illustrates the fact that salt accumulation is not only a function of distance from the coast but also depth of water; this highlights the importance of assessing the combination of distance offshore and depth of water that minimizes salt accumulation during the planning and design of future seawater desalination plants, as well the management of current plants.

Lastly, the fourth main contribution of this thesis reported in chapter 7 is the trend analysis of Gulf water surface elevation, temperature and salinity that shows a significant trend in Gulf water temperature and a slight trend in Gulf salinity. Satellite derived water surface elevation and sea surface temperature are used for the analysis of trends in the Gulf for the period 1993 - 2014. Observed salinity data for the Gulf is sparse, and in order to overcome this scarcity of salinity data, regression models of salinity as a function of water surface elevation and temperature, developed from three different numerical experiments in which the dynamics of the residual circulation in the Gulf is simulated in the GARM, are used with satellite derived water surface elevation and SST to compute trends in salinity for the same period.

Gulf water elevation increased by 3.3 mm/yr (72.6 mm/22yrs), while Gulf seas surface temperature increased by 0.09°C/yr (1.9°C/22yrs). The four regression models used to compute the trend of Gulf salinity show a decreasing trend in Gulf salinity: RM1 (-0.009 g/kg/yr and -0.20 g/kg/22yrs); RM2 (-0.0071 g/kg/yr and -0.16 g/kg/22yrs); RM3 (-0.007 g/kg/yr and -0.15 g/kg/22yrs); RM4 (-0.0071 g/kg/yr and -0.16 g/kg/22yrs). And the consistent sign of the salinity trends increase confidence in the regression models used to estimate trends in Gulf salinity. The trends for Gulf water surface elevation, salinity and temperature are all within the 95% and 90% acceptance zone for each variable, which suggests that these trends probably reflect real trends but of small magnitude. However, the Gulf trends may also be due to dynamic response to the positive trend of Indian Ocean water elevation, which results in higher transport into the Gulf and increased mixing of Gulf waters, reduction in Gulf salinity, and increase in Gulf water elevation.
8.2 Future Research Directions in the Persian Gulf

A future direction of research that builds on the contributions of this thesis is the investigation of the sensitivity of marine life, in different regions within the Gulf, to the various constituents of brine discharge from seawater desalination plants. The work in this thesis shows that brine discharge from desalination plants has minimal impact on the basin averaged salinity but significant impact on regional salinities, and change in regional salinities is used to identify regions with the largest salt accumulation due to brine discharge from seawater desalination plants. This finding is important for ecological studies of the effect of brine discharge from desalination plants in the Gulf because it identifies regions for monitoring limiting environmental parameters such as the maximum, minimum and optimal limits for survival and successful reproduction. Changes in any one of these limits may have a significant impact on the ecological viability of the Gulf, and not only are these limits important for salt, but also for the other constituents of brine such as metal ions and chlorinated hydrocarbons, which may have detrimental effects on marine life at lower levels of exposure relative to salt.

Another direction of future research that extends the findings in this thesis is the impact of climate change on the residual circulation between the Gulf and the Indian Ocean, and the consequent effect on the interaction between brine discharge from seawater desalination plants and the residual circulation. The Gulf is strongly coupled to the atmosphere and Indian Ocean because the Gulf is shallow with extremely high evaporation rates that drive the residual circulation between the Gulf and the Indian Ocean. And because the residual circulation restores Gulf density if it is perturbed, climate change is unlikely to have a significant effect on the basin scale residual circulation, and thus, the basin averaged salinity of the Gulf. However, climate change may have a significant effect on the spatiotemporal variation of the residual circulation within the Gulf; and since the interaction of coastal currents in the Gulf and the residual circulation within the Gulf determines the regions of salt accumulation due to brine discharges from seawater desalination plants, it follows that climate change may have a significant effect on the regional distribution of salt accumulation due to brine discharges from seawater desalination plants in the Gulf.
Appendix A

Gulf Current Climate

<table>
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<tr>
<th>Experiment</th>
<th>Mean basin salinity (g/kg)</th>
<th>Mean basin temperature (°C)</th>
<th>Comments</th>
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</thead>
<tbody>
<tr>
<td>Ic1</td>
<td>40.1</td>
<td>21.4</td>
<td>+ Spatial variability</td>
</tr>
<tr>
<td>Ic2</td>
<td>24.8</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>Ic3</td>
<td>42.6</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>Ic4</td>
<td>38.0</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>Ic5</td>
<td>39.0</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>Ic6</td>
<td>40.0</td>
<td>24.8</td>
<td></td>
</tr>
</tbody>
</table>

Figure A-1: Initial salinity and temperature for all equilibrium experiments; all experiments, except Ic1, were started with a constant salinity and temperature. Ic1 was started with spatially variable initial salinity with mean 40.1 g/kg, and spatially variable temperature with mean 21.4°C.
Figure A-2: Gulf evaporation for all six equilibrium experiments

Figure A-3: Gulf precipitation for all six equilibrium experiments
Figure A-4: Gulf net shortwave for all six equilibrium experiments

Figure A-5: Gulf sensible heat for all six equilibrium experiments
Figure A-6: Gulf wind stress for all six equilibrium experiments

Figure A-7: Gulf albedo for all six equilibrium experiments
Figure A-8: Indian Ocean temperature at different depths

Figure A-9: Gulf sensible heat and water surface temperature for all six equilibrium experiments
Figure A-10: Gulf sensible heat and air (2m) temperature for all six equilibrium experiments
References


